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## ExternE National Implementation for Denmark

Lotte Schleisner and Per Sieverts Nielsen



Risø National Laboratory, Roskilde, Denmark
December 1997

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# External Costs Related to Power Production Technologies

## ExternE National Implementation for Denmark

**Lotte Schleisner, Risø National Laboratory**
**Per Sieverts Nielsen, Technical University of Denmark**

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**FINAL REPORT**
December 1997

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**THE EUROPEAN COMMISSION**
in the framework of the Non Nuclear Energy Programme
**JOULE III**

**Risø National Laboratory, Roskilde, Denmark**
**December 1997**

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# CONTRIBUTORS

Lotte Schleisner, Risø National Laboratory and Per Sieverts Nielsen, The Technical University of Denmark, have prepared this report.

Concerning the preparation Per Sieverts Nielsen is responsible for the work done considering the biogas case, while Lotte Schleisner is responsible for the work done considering the wind case. The natural gas case has been prepared jointly.

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# CONTENTS

# EXECUTIVE SUMMARY

## Introduction

### Background and objectives

The use of energy causes damage to a wide range of receptors, including human health, natural ecosystems, and the built environment. Such damages are referred to as external costs, as they are not reflected in the market price of energy. These externalities have been traditionally ignored.

However, there is a growing interest towards the internalisation of externalities to assist policy and decision making. Several European and international organisms have expressed their interest in this issue, as may be seen in the 5th Environmental Action Programme, in the White Paper on Growth, competitiveness and employment, or the White Paper on Energy, all from the European Commission. This interest has led to the development of internationally agreed tools for the evaluation of externalities, and to its application to different energy sources.

Within the European Commission R&D Programme Joule II, the ExternE Project developed and demonstrated a unified methodology for the quantification of the externalities of different power generation technologies. Under Joule III, this project has been continued with three distinguished major tasks: ExternE Core for the further development and updating of the methodology, ExternE National Implementation to create an EU-wide data set and ExternE-Transport for the application of the ExternE methodology to energy related impacts from transport. The current report is the result of the ExternE National implementation project for Denmark.

The objective of the ExternE National Implementation project is to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The tasks include the application of the ExternE methodology to the most important fuel cycles for each country as well as to update the already existing results; to aggregate these site- and technology-specific results to more general figures. For countries already involved in Joule II, these data have been applied to concrete policy questions, to indicate how these data could feed into decision and policy-making processes. Other objectives were the dissemination of results in the different countries, and the creation of a network of scientific institutes familiar with the ExternE methodology, data, and their application.

The National Implementation project has generated a large set of comparable and validated results, covering more than 60 cases, for 15 countries and 11 fuel cycles. A wide range of technologies have been analysed, including fossil fuels, nuclear and renewables. Fuel cycle analyses have been carried out, determining the environmental burdens and impacts of all stages. Therefore, besides from the externalities estimated, the project offers a large database of environmental aspects of the fuel cycles studied.

An aggregation exercise has also been carried out, to extend the analysis to the whole electricity system of each of the participant countries. The exercise has proved to be very useful, although the results must be considered in most cases as a first approach, which should be carefully revised before being taken into consideration.

In spite of all the uncertainties related to the externalities assessment, the output of the project might prove to be very useful for policy-making, both at the national and EU level. The results obtained provide a good basis to start the study of the internalisation of the external costs of energy, which has been frequently cited as one of the objectives of EU energy policy. Other possibility is to use the results for comparative purposes. The site sensitivity of the externalities might encourage the application of the methodology for the optimisation of site selection processes, or for cost-benefit analysis of the introduction of cleaner technologies. The usefulness of the application for policy making has been demonstrated through the analysis of a wide variety of decision making issues carried out by those teams already involved in ExternE under Joule II.

Further work is needed, however, to remove as much uncertainties as possible of the methodology, and to improve aggregation methods for electricity systems. These improvements are required if externality values are to be used directly for policy measures, not only as background information. The acceptability of these measures will depend on the credibility of the externality values.

The current report is to be seen as a larger set of publications. The results of these ExternE projects are published and made available in three different reports and publications. The current report covers the results of the national implementation for Denmark and is published by Risø National Laboratory. For Denmark three different fuel cycles have been chosen as case studies. These are fuel cycles for an offshore wind farm and a wind farm on land, a decentralised CHP plant based on natural gas and a decentralised CHP plant based on biogas. The report covers all the details of the application of the methodology to these fuel cycles and aggregation to a national level. The methodology is detailed in a separate report, published by the EC.

**The Danish national implementation**

Denmark is a small country placed in the Northern Europe. It comprises the peninsula of Jutland, the islands of Zealand, Funen, Lolland, Falster and Bornholm, and 401 minor islands. The North Sea to the west and the Baltic Sea to the east border the country. Denmark borders on Germany to the south, this being its only land frontier. Denmark covers a total area of 43,094 $km^2$ and has a total population of 5.2 mill. inhabitants.

Although the energy consumption has been stable during the last 20 years, there have been large displacements in the type of fuel used as well as patterns of consumption. Increased co-production of electricity and heat, and conversion of fuels from oil and coal to natural gas and renewable energy, has begun to make a clear impact on the Danish energy supply sector.

The three power plant technologies, which have been analysed in the project, are an offshore wind farm, a decentralised CHP plant based on natural gas and a decentralised CHP plant based on biogas. All of the three kinds of plants are important in the Danish Energy Plan, and therefore during the next years these plants will become more and more common in Denmark. For aggregation, however, it has been necessary to include a wind farm on land.

The locations of the different plants are shown in Figure 1.

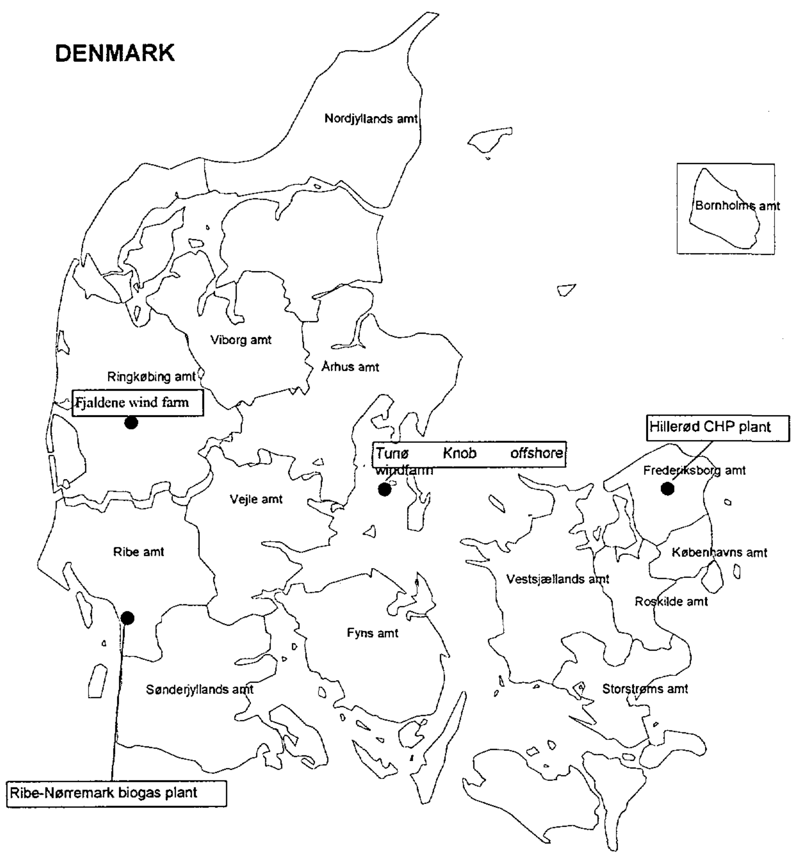


**Figure 1** Location of the energy production plants

Denmark has been the first country in the world to establish an offshore wind farm. Today there are two such wind farms in Denmark, each with a capacity of 5 MW. One of them has been in operation since 1991 and the other since October 1995. The newest of the wind farms has been chosen for the externality case study, as this wind farm focuses on the environmental impacts.

Biogas is produced in different kinds of plants in Denmark, among others individual plants, smaller farmer plants and collective plants. The biogas is used for CHP production. Today about 20 collective biogas plants are operating in larger scale, half of which are demonstration plants. The plants demonstrate the possibilities for reaching environmental and agricultural advantages together with an energy production based on biogas. The plants have today a very stable biogas production. One of the larger collective biogas plants has been chosen as a case study in the project.

In Denmark CHP production based on natural gas is becoming more and more common. In 1994 69% of the total district heating production was based on CHP plants. 20% of these are decentralised plants based on natural gas or waste combustion. One of the largest decentralised natural gas CHP plants has been chosen for the case study.

## Methodology

The methodology used for the assessment of the externalities of the fuel cycles selected has been the one developed within the ExternE Project *(CEC, 1995 a-f)*. It is a bottom-up methodology, with a site-specific approach, that is, it considers the effect of an additional fuel cycle, located in a specific place.

To allow comparison to be made between different fuel cycles, it is necessary to observe the following principles:

- Transparency, to show precisely how the work was done, the uncertainty associated to the results, and the extent to which the external cost of any fuel cycle have been fully quantified.
- Consistency, with respect to the boundaries placed on the system in question, to allow valid comparison to be made between different fuel cycles and different types of impact within a fuel cycle.
- Comprehensiveness, to consider all burdens and impacts of a fuel cycle, even though many may be not investigated in detail. For those analysed in detail, it is important that the assessment is not arbitrarily truncated.

These characteristics should be present along the stages of the methodology, namely: site and technology characterisation, identification of burdens and impacts, prioritisation of impacts, quantification, and economic valuation.

Quantification of impacts is achieved through the damage function, or impact pathway approach. This is a series of logical steps, which trace the impact from the activity that creates it to the damage it produces, independently for each impact and activity considered, as required by the marginal approach.

The underlying principle for the economic valuation is to obtain the willingness to pay of the affected individuals to avoid a negative impact, or the willingness to accept the opposite. Several methods are available for this, which will be adopted depending on the case.

## Overview of the fuel cycles assessed

### Natural gas fuel cycle

In Denmark combined heat and power (CHP) is an important way of producing heat either in central plants or in smaller decentralised plants. This results in a higher total energy efficiency. For this reason traditional district heating plants are gradually being replaced by CHP. In 1994 60% of the district heating production was based on CHP plants. 20% of the CHP production was based on decentralised plants *(The Danish Energy Agency, 1994).* By the beginning of 1996, a total capacity of about 1300 $MW_{el}$ decentralised CHP plants had been established *(The Danish Energy Agency, 1995).*

In 1986 a political decision was made between the Government and the electric utilities concerning future expansion of the electricity supply in Denmark. The agreement included a decision to establish decentralised CHP plants based on Danish energy sources with a total electric capacity of 450 MW before the end of 1995. According to the decision the expansion of decentralised combined heat and power must be based on Danish energy sources such as natural gas, waste or biofuels (straw, wood or biogas). Coal and oil may be used only as peak load or spare load fuel. The status of the extension of decentralised CHP for the different fuels is shown in Figure 2.

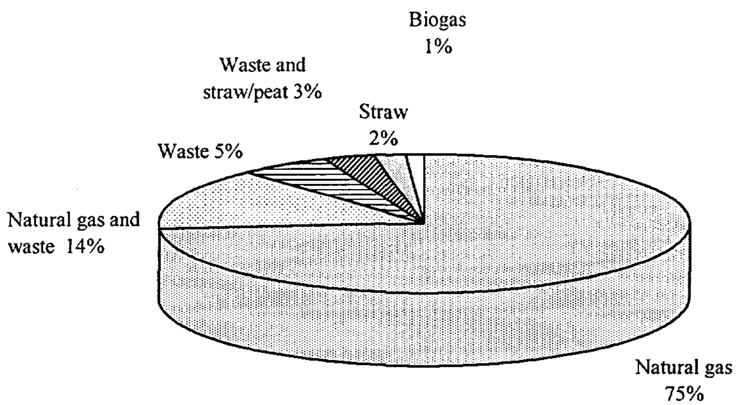


**Figure 2** Decentralised CHP based on different fuels *(The Danish Energy Agency, 1995)*

The figure illustrates that natural gas is by far the most important fuel, either alone or together with waste.

Table 1 shows key numbers for the decentralised CHP plants in Denmark. The table includes existing plants as well as plants planned until the year 1998.

**Table 1** Key numbers for decentralised CHP plants *(The Danish Energy Agency, 1993)*

| | Gas motor | Gas turbine | Combined cycle | Boiler/ steam turbine | Total |
|---|---|---|---|---|---|
| Total number | 217 | 10 | 10 | 23 | 260 |
| Electricity (MW) | 560 | 67.3 | 480 | 183.7 | 1291 |
| Heat (MJ/s) | 716 | 117 | 466.5 | 452.5 | 1752 |

Although only 10 out of 260 plants are combined-cycle plants, this technology covers more than one-third of the electricity capacity. The combined-cycle technology seems in this way to be an important technology in the future. Therefore a combined-cycle CHP plant has been chosen as a case study for the natural gas fuel cycle in the ExternE study.

Hillerød CHP plant has been selected as case study for the natural gas fuel cycle, being one of the decentralised plants with the largest capacity and also the highest $C_m$ value (the ratio between electricity production and CHP production at maximum heat production). Hillerød plant has been in operation since 1991 and operational data are available.

**Biogas fuel cycle**

Biogas is a product of anaerobic digestion where organic wastes (particulate organic matter) are converted by fermentative, acetogenic and methanogenic bacteria into methane ($CH_4$). The process involves three different stages: First, the fermentative bacteria hydrolyses and ferments the organic matter into fatty acids, alcohol, carbon dioxide, ammonia and sulphides. In the second stage, these products are consumed by acetogenic bacteria, and hydrogen, carbon dioxide and acetic acids are produced. The third stage involves two different kinds of methanogenic bacteria. One reduces carbon dioxide to methane, and the other converts decarboxylates acetic acid to $CH_4$ and carbon dioxide *(C.C. Ross et al, 1996).*

The $CH_4$ production increases with temperature, but temperatures between 35°C and 55°C are regarded to be optimal for biogas production. Using temperatures at 35°C the process is called mesophillic, which is often preferred due to a lower heat demand for heating the biomass. However, when it is used in joint biogas plants, the low-temperature process needs to be heated for hygienisation at 70°C for 2 hours. Using the higher reactor temperature of 55°C (thermophillic process) the hygenisation is avoided, but the higher temperature is then maintained during the biogas production process (12-20 days). Due to the anaerobic processes the digestion processes themselves do not produce heat, which means that the processes have to get all their heat supplied from external sources (by heat exchange or heat supply).

Organic waste from agriculture, here in the pure form called slurry (cattle and/or swine slurry), is in this study the basic source for producing biogas. The slurry or the organic matter of slurry is, however, at varying degrees of methane-convertibility and in fact only a relatively small fraction of the organic matter is easily convertible into $CH_4$. A theoretical yield is a production of 30-40 $m^3$ biogas/t biomass.

The fraction of the carbon in waste, which is easily convertible into CH4, is larger in industrial organic wastes such as organic wastes from slaughterhouses. By mixing slurry with industrial organic wastes one to five it is possible to almost double the production of biogas per t of biomass. This has been one of the main reasons for development of the joint biogas plants in Denmark in the last decade where it has become economical to utilise the industrial organic waste. Farmers offer their slurry to a biogas plant where it is mixed with organic wastes, biogas is produced for energy purposes and the farmer received back in principle as much digested biomass as he wants.

Presently there is a large production of slurry in the Danish agriculture. But the production of organic waste in the industry is limited. The bulk of the slurry is produced at large conventional farms with specialised cattle, dairy or pig farming. The specialisation in the Danish agricultural sector means that slurry has to be exchanged between farmers to fulfil the national regulation on harmonisation, i.e. not more than one cow to one ha of land. The legislation on harmonisation is a national environmental policy for reducing nitrate leaching on agricultural lands in Denmark, which is the main focus on environmental impacts of slurry production today in Denmark.

Some other practical reasons for establishing joint biogas plants have been to obtain more homogenic biomass manure, which more easily and more effectively can be spread on the agricultural fields.

In this report, for clarification slurry is referred to as "raw" non-digested or non-fermented organic matter from pig, cattle, dairy or poultry farms. Industrial organic waste is "waste" mainly from food processing industries, slaughterhouses etc. Non-digested or non-fermented biomass refers to the mix of slurry and industrial organic waste before it enters into the reactors. Digested or fermented biomass refers to the mix of biomass coming out of the reactor. Biomass always refers to a mix of different "waste" sources.

The biogas fuel cycle described in the report is a large joint biogas plant in Denmark, Ribe Biogas Plant (RBP). RBP is one of the 19 large joint biogas plants in the country and produces biogas on slurry from 79 farms. It was established in 1990 and is owned by Ribe Biogas A/S (Shareholder Company). The shares are owned by Landmændenes Leverandørorganisation (a co-operation of the farmers supplying the slurry), Vestjyske Slagterier, Sønderjyllands Højspændingsværk, Hafnia Invest and ATP-fonden. The connected Ribe-Nørremark Combined Heat and Power (R-NCHP) Plant is owned by Sønderjyllands Højspændingsværk.

### Wind fuel cycle

In 1995 about 8% of the energy production in Denmark was covered by renewable energy. Wind power produced about 5% of the total electricity production. Ultimo 1996, 825 MW wind power have been estimated to be installed *(Danish Wind Turbine Manufacturers Association, 1997)*. It is the intention to extend the wind power to 1700 MW by the year 2005, of which 310 MW will be offshore.

There is a large amount of unused wind resources in Denmark as well on land as offshore. On land, however, areas with good wind conditions are limited due to the size of the country, its relatively high population density, and the disposal of areas for forestry, bird protection areas, and industry. For all these reasons Denmark constructed the world's first offshore wind farm in 1991, and today two such wind farms are in operation.

Both of the existing offshore wind farms, Vindeby wind farm close to Lolland and Tunø Knob wind farm close to the East Coast of Jutland, have been established as demonstration projects. Vindeby wind farm was established with the purpose of investigating the technical and economic conditions concerning offshore wind energy, while Tunø Knob wind farm also was intended to investigate the wind turbine effect on the environment in the area.

Taking this in consideration Tunø Knob will be the most obvious wind farm to select as a case study for the offshore wind fuel cycle in the ExternE study. At Tunø Knob investigations concerning the environment are already being made for the following areas:

- Ornithologists are investigating the lives of both birds and shells in the area.
- Archaeologists have dived after ship wrecks and Stone Age residences.
- Biologists have searched for threatened nature types on the seabed.
- Hydrologists have mapped current conditions.
- Landscape architects have visualised the offshore wind turbines.
- The electrical utility has made calculations of noise.

All these investigations concerning the environment will be important in relation to the assessment of environmental impacts of offshore wind farms.

For aggregation it will be necessary also to include a case study for an ordinary wind farm on land. The wind farm that has been chosen as the case on land is Fjaldene wind farm located in the middle of Jutland. It has been selected because it is quite similar to the Tunø Knob system in size and type of turbines.

## Aggregation

The preferred methodology for aggregation is to use an updated version of EcoSense, which is able to include various energy production plants. However, this version of EcoSense is unavailable for the time being, and a simplified methodology for aggregation has been used. The simplified methodology uses the marginal values from ExternE in rather simple calculations to derive aggregate damage values.

The electricity production and combined electricity and heat production have been divided into categories, following the plants for which damage costs have been estimated in the Danish implementation.

Although the estimation of the damages of an individual fossil power plant is not so complex, the addition of the damages caused by various plants poses a lot of difficulties, because of the site-specificity of results, and the alterations produced by background pollutant emissions.

## Conclusion

This report is the first comprehensive attempt to estimate the externalities of electricity generation in Denmark using a common EU methodology. Hence, it is believed that it will contribute to a large extent to the integration of environmental aspects into energy policy. The major result of this study is that, in spite of the uncertainties underlying the analysis, a large set of externalities for electricity generation has been calculated. Therefore, a first attempt towards the integration of environmental aspects into energy policy may be carried out, taking into account all the limitations which will be explained later.

However, due to the limitations mentioned before, it is recommended to use the results provided by this report only as background information. This background information might be very useful for establishing economic incentives, such as environmental taxes, or subsidies for renewable energies, or for energy planning measures. However, results should not be used directly, until the methodology is refined.

For what results may be used directly, though, is for planning processes where the quantitative results are not so relevant. This is the case, for example, of the optimisation of plant site selection, or for choosing among different energy alternatives. Another possible use of these results is the analysis of the costs and benefits of the implementation of environmentally friendly technologies.

# 1. INTRODUCTION

Economic development of the industrialised nations of the world has been founded on continuing growth in energy demand. The use of energy clearly provides enormous benefits to society. However, it is also linked to numerous environmental and social problems, such as the health effects of pollution of air, water and soil, ecological disturbance and species loss, and landscape damage. Such damages are referred to as external costs, as they have typically not been reflected in the market price of energy, or considered by energy planners, and consequently have tended to be ignored. Effective control of these 'externalities' whilst pursuing further growth in the use of energy services poses a serious and difficult problem. The European Commission has expressed its intent to respond to this challenge on several occasions; in the 5th Environmental Action Programme; the White Paper on Growth, Competitiveness and Employment; and the White Paper on Energy.

A variety of options are available for reducing externalities, ranging from the development of new technologies to the use of fiscal instruments, or the imposition of emission limits. The purpose of externalities research is to quantify damages in order to allow rational decisions to be made that weigh the benefits of actions to reduce externalities against the costs of doing so.

Within the European Commission R&D Programme Joule II, the ExternE Project developed and demonstrated a unified methodology for the quantification of the externalities of different power generation technologies. It was launched as the EC-US Fuel Cycles Study in 1991 as a collaborative project with the US Department of Energy. From 1993 to 1995 it continued as the ExternE project, involving more then 40 European institutes from 9 countries, as well as scientists from the US. This resulted in the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a wide range of different fuel chains. The result was identified by both the European and American experts in this field as currently the most advanced project world-wide for the evaluation of external costs of power generation (EC/OECD/IEA, 1995).

Under the European Commission's Joule III Programme, this project has continued with three major tasks: ExternE Core for the further development and updating of the methodology, ExternE National Implementation to create an EU-wide data set and ExternE-Transport for the application of the ExternE methodology to energy related impacts from transport. The current report is the result of the ExternE National implementation project for Denmark.

## 1.1 Objectives of the project

The objective of the ExternE National Implementation project is to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The tasks include;

- the application of the ExternE methodology to the most important fuel chains for each country
- updating existing results as new data become available for refinement of methods
- aggregation of site- and technology-specific results to the national level
- for countries already involved in Joule II, data have been applied to policy questions, to indicate how these data could feed into decision and policy making processes
- dissemination of results
- creation of a network of scientific institutes familiar with the ExternE methodology and data, and their application
- compilation of results in an EU-wide information system for the study.

The data in this report results from the application of ExternE-methodology as developed under Joule II. However, because our understanding of the impacts of environmental burdens on humans and nature is improving continuously, this methodology (or more precise, the scientific inputs into the accounting framework) has been updated and further developed.

The National Implementation project has generated a large set of comparable and validated results, covering more than 60 cases, for 15 countries and 12 fuel chains. A wide range of generating options has been analysed, including fossil, nuclear and renewable technologies. Analysis takes account of all stages of the fuel chain, from (e.g.) extraction of fuel to disposal of waste material from the generating plant. In addition to the estimates of externalities made in the study, the project also offers a large database of physical and social data on the burdens and impacts of energy systems.

The ExternE results form the most extensive externality data set currently available. They can now be used to look at a range of issues, including;

- internalisation of the external costs of energy
- optimisation of site selection processes
- cost benefit analysis of pollution abatement measures
- comparative assessment of energy systems

Such applications are illustrated by the case studies presented later in this report, and in other national implementation reports.

## 1.2 Publications from the project

The current report is to be seen as part of a larger set of publications, which commenced with the series of volumes published in 1995 (European Commission, 1995a-f). A further series of reports has been generated under the present study.

First, the current report covers the results of the national implementation for Denmark and is published by Risø National Laboratory. It contains all the details of the application of the methodology to the selected fuel cycle cases, wind, natural gas and biogas and for aggregation. Brief details of the methodology are provided in Chapter 2 of this report and the Appendices; a more detailed review is provided in a separate report (European Commission, 1998a). A further report covers the development of estimates of global warming damages (European Commission, 1998b). The series of National Implementation Reports for the 15 countries involved are published in a third report (European Commission, 1998c).

In addition, further reports are to be published on the biomass and waste fuel chains, and on the application and further development of the ExternE methodology for the transport sector.

This information can also be accessed through the ExternE website. It is held at the Institute for Prospective Technological Studies, and is accessible through the Internet (*http://externe.jrc.es*). This website is the focal point for the latest news on the project, and hence will provide updates on the continuation of the ExternE project.

## 1.3 Structure of this report

The structure of this report reflects that it is part of a wider set of publications. In order to ease comparison of results, all ExternE National Implementation reports have the same structure and use the same way of presentation of fuel cycles, technologies and results of the analysis.

The common structure is especially important for the description of the methodology. Chapter 2 describes the general framework of the selected bottom-up methodology. The major inputs from different scientific disciplines into that framework (e.g. information on dose-response functions) are summarised in the methodological annexes to this report and are discussed at full length in the separate methodology publication (see above).

In order to ease readability, the main text of the chapters dealing with the application to the different fuel cycles provide the overview of technology, fuel cycles, environmental burdens and the related externalities. More detailed information (e.g. results for a specific type of impact) is provided in the appendices.

## 1.4 The Danish National Implementation

### 1.4.1 Description of the country

***Location, language and religion***

Denmark is a small country with a total area of 43,094 $km^2$. In 1996 the population density was 121.9 inhabitants per $km^2$ with a total population of 5.251 mill. inhabitants. In the past ten years the population has increased by less than 0.03 percent, while the average population growth rate from 1940 until the present has been 0.6% p.a.

Denmark is a kingdom situated in northern Europe. It comprises the peninsula of Jutland, the islands of Zealand, Funen, Lolland, Falster and Bornholm, and 401 minor islands. The North Sea to the west and the Baltic Sea to the east border the country. Denmark borders on Germany to the south, this being its only land frontier. Norway is situated to the north of Denmark separated by Skagerrak, while Sweden lies to the northeast. Southern Sweden is separated from the Danish island of Zealand only by a narrow strait. Outlying territories of Denmark include Greenland and the Faeroe Islands in the northern part of the Atlantic.

The official language is Danish. The majority of the population professes Christianity and 87% of the population are members of the established Lutheran church. Small communities of other Protestant groups and of Roman Catholics represent other denominations.

### *Climate*

Denmark is a low-lying country and the climate is temperate with mild summers and cold, rainy winters. The annual mean temperature is 8.2 °C, mean rainfall is 652 mm and mean wind speed is 7.4 m/s. The monthly mean values for these parameters are shown in Figure 1.1.

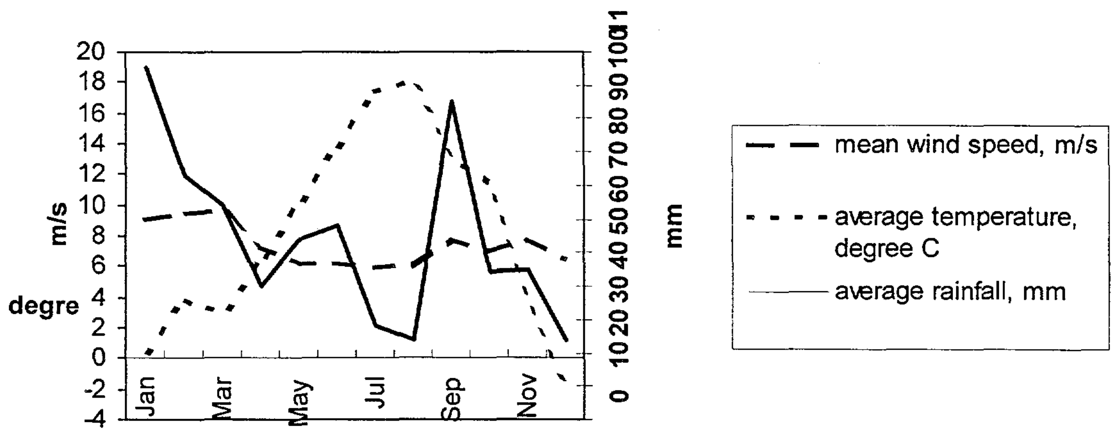


**Figure 1.1** Monthly mean values for temperature, rainfall and wind speed, 1995

## 1.4.2 Overview of the Danish energy sector

The energy consumption in Denmark has been almost constant during the last 20 years at an amount of about 800 PJ. This accounts for about 2.3 ‰ of the global energy consumption, while the population is only 1‰ of the world total.

Although the energy consumption has been stable, there have been large displacements in the type of fuel used as well as patterns of consumption. Increased co-production of electricity and heat, and conversion of fuels from oil and coal to natural gas and renewable energy, has begun to make a clear impact on the Danish energy supply sector.

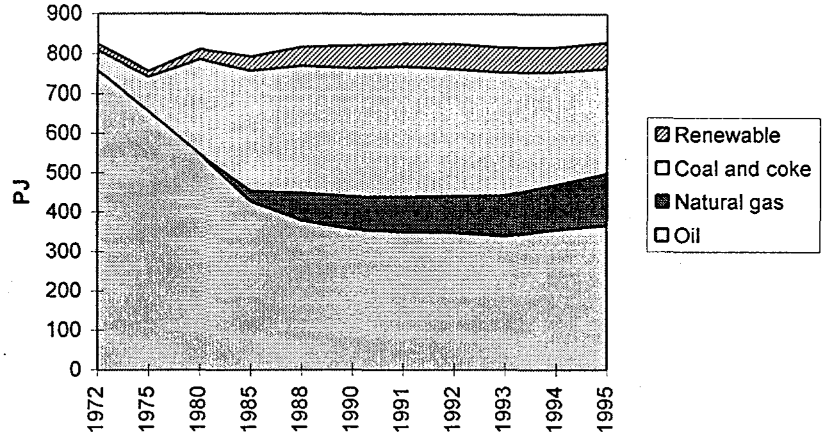


**Figure 1.2** Gross energy consumption by fuel 1972-1995 *(Danish Energy Agency, 1996)*

Consumption of coal has fallen at power stations and district heating plants as well as in the primary and secondary production sectors. Conversion from oil to natural gas and district heating means that oil consumption has been falling year after year. During the last two years, however, oil consumption has increased mostly because of the use of Orimulsion for CHP production. Also there has been an increasing consumption of oil in the transportation and production sectors.

Since 1989 consumption of natural gas has gone up by 5 PJ a year and sales to district heating plants, small-scale CHP plants and households have risen. On the other hand, there has been little or no change in consumption of natural gas in industry and other manufacturing enterprises during recent years.

Consumption of renewable energy has grown considerably since the beginning of the 1980s. After two years of stagnation consumption again rose in 1995 and renewable energy covers now 7.8% of the total energy demand.

The energy supply and demand for Denmark in 1995 is shown in Figure 1.3.

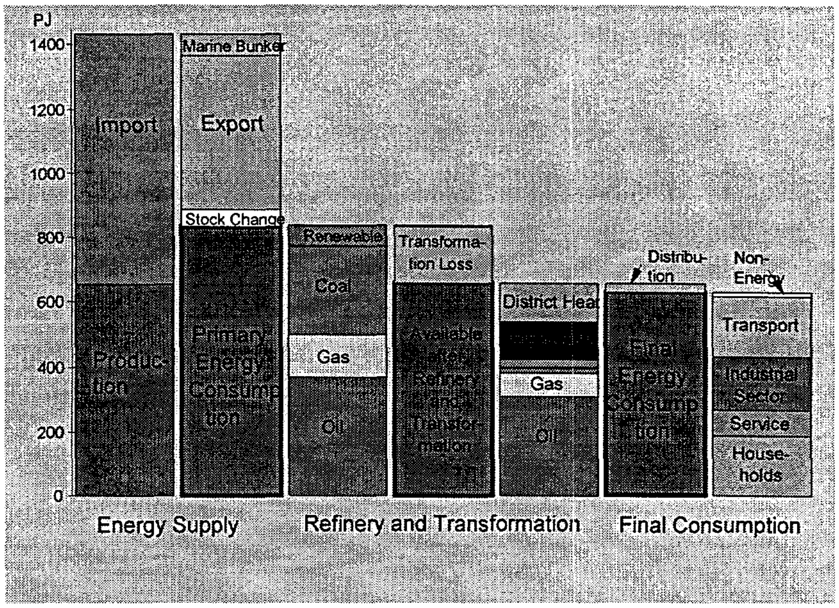


**Figure 1.3** Energy supply and demand for Denmark, 1995 *(Danish Energy Agency, 1996)*

The main 1995 figures, for the energy sector are shown in Table 1.1. In 1995 the electricity production in Denmark was 117 PJ. 10.3% of the electricity was produced at decentralised CHP plants and 3.6% by wind power.

**Table 1.1** Main figures and key indicators of energy

| | Main figures, 1995 |
|---|---|
| *Primary Energy Consumption, PJ* | *829* |
| Renewable Energy etc, % | 7.8 |
| *Primary Production, PJ* | *655* |
| Oil, PJ | 392 |
| Natural Gas, PJ | 197 |
| Renewable Energy etc, PJ | 65 |
| *Production of Electricity, PJ* | *117* |
| Small-scale CHP Plants, % | 10.3 |
| Wind Power, % | 3.6 |
| *Production of District Heat, PJ* | *116* |

# 2. METHODOLOGY

## 2.1 Approaches Used for Externality Analysis

The ExternE Project uses the 'impact pathway' approach for the assessment of the external impacts and associated costs resulting from the supply and use of energy. The analysis proceeds sequentially through the pathway, as shown in Figure 2.1. Emissions and other types of burden such as risk of accident are quantified and followed through to impact assessment and valuation. The approach thus provides a logical and transparent way of quantifying externalities.

However, this style of analysis has only recently become possible, through developments in environmental science and economics, and improvements in computing power has. Early externalities work used a 'top-down' approach (the impact pathway approach being 'bottom-up' in comparison). Such analysis is highly aggregated, being carried out at a regional or national level, using estimates of the total quantities of pollutants emitted or present and estimates of the total damage that they cause. Although the work of Hohmeyer (1988) and others advanced the debate on externalities research considerably, the style of analysis was too simplistic for adoption for policy analysis. In particular, no account could be taken of the dependence of damage with the location of emission, beyond minor corrections for variation of income at the valuation stage.

An alternative approach was the 'control cost' method, which substitutes the cost of reducing emissions of a pollutant (which are determined from engineering data) for the cost of damages due to these emissions. Proponents of this approach argued that when elected representatives decide to adopt a particular level of emissions control they express the collective 'willingness-to-pay' of the society that they represent to avoid the damage. However, the method is entirely self-referencing - if the theory were correct, whatever level of pollution abatement is agreed would by definition equal the economic optimum. Although knowledge of control costs is an important element in formulating prescriptive regulations, presenting them as if they were damage costs is to be avoided.

Life cycle analysis *(OECD, 1992; Heijungs et al, 1992; Lindfors et al, 1995)* is a flourishing discipline whose roots go back to the net energy analyses that were popular twenty years ago. While there are several variations, all life cycle analysis is in theory based on a careful and holistic accounting of all energy and material flows associated with a system or process. The approach has typically been used to compare the environmental impacts associated with different products that perform similar functions, such as plastic and glass bottles. Restriction of the assessment to material and energy flows means that some types of externality (such as the fiscal externalities arising from energy security) are completely outside the scope of LCA.

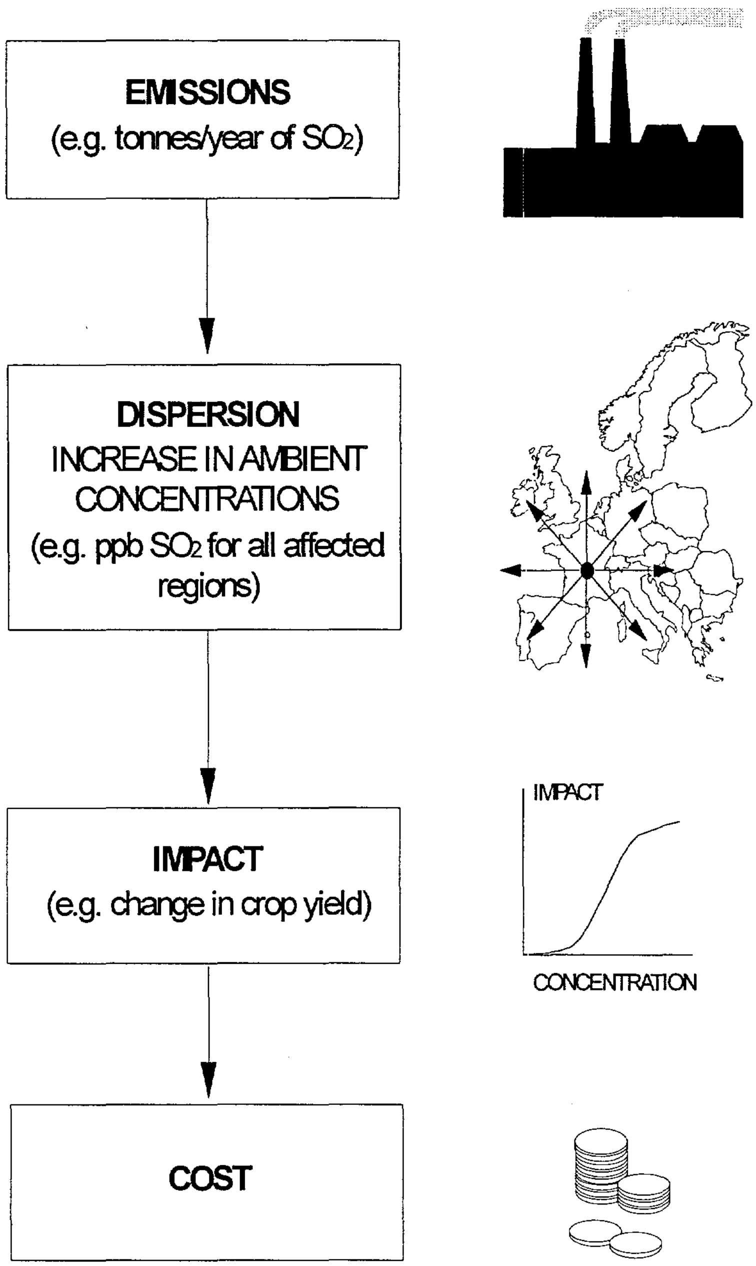


**Figure 2.1** An illustration of the main steps of the impact pathways methodology applied to the consequences of pollutant emissions. Each step is analysed with detailed process models.

The ExternE method has numerous links to LCA. The concept of fuel cycle or fuel chain analysis, in which all components of a given system are analysed 'from cradle to grave', corresponds with the LCA framework. Hence for electric power fuel chains the analysis undertaken within the ExternE Project covers (so far as possible); fuel extraction, transportation and preparation of fuels and other inputs; plant construction, plant operation (power generation), waste disposal and plant decommissioning.

There are, however, some significant differences between externalities analysis as presented in this study and typical LCA analysis. Life cycle analyses tend not to be specific on the calculation of impacts, if they have attempted to quantify impacts at all. For example, the 'classification factors' identified by Heijungs *et al* (1992) for each pollutant are independent of the site of release. For air pollution these factors were calculated with the assumption of uniform mixing in the earth's atmosphere. While this can be justified for greenhouse gases and other pollutants with long residence times, it is unrealistic for particulate matter, $NO_x$, $SO_2$ and ozone ($O_3$). The reason for this radical approximation lies in the choice of emphasis in LCA: accounting for all material flows, direct and induced. Since induced flows occur at many geographically different points under a variety of different conditions, it is simply not practicable to model the fate of all emissions. In this sense, ExternE is much more ambitious and precise in its estimates than LCA.

A second difference is that most LCA studies have a much more stringent view on system boundaries and do not prioritise between different impacts. The ExternE analysts have to a large extent decided themselves if certain stages of the fuel cycle, such as plant construction or fuel transportation, can be excluded. Such decisions are made from experience of the likely magnitude of damages, and knowledge of whether a given type of impact is *perceived* to be serious. [Note that it is recommended to quantify damages for any impact perceived to be serious whether or not earlier analysis has suggested that associated damages will be negligible]. What might be referred to as analytical 'looseness' is a consequence of the remit of the ExternE project, which has as a final objective quantification of the externalities of energy systems. As such the main emphasis of the study is quite properly on the impacts that are likely (given current knowledge) to dominate the results. Externalities assessments based on the ExternE methodology but conducted for other purposes may need to take a more truly holistic perspective than has been attempted here.

The analysis presented in this report places its emphasis on the quantification of impacts and cost because people care more about impacts than emissions. The quantification of emissions is merely a step in the analysis. From this perspective the choice between externalities assessment and conventional LCA is a matter of accuracy; uncertainties increase the further the analysis is continued. In general terms, however, it is our view that the fuel chain analyses of the ExternE Project can be considered a particular example of life cycle analysis.

## 2.2 Guiding Principles in the Development of the ExternE Methodology

The underlying principles on which the methodology for the ExternE Project has been developed are:

***Transparency***, to show precisely how results are calculated, the uncertainty associated with the results and the extent to which the external costs of any fuel chain have been fully quantified.

***Consistency***, of methodology, models and assumptions (e.g. system boundaries, exposure-response functions and valuation of risks to life) to allow valid comparisons to be made between different fuel chains and different types of impact within a fuel chain.

***That analysis should be comprehensive***, we should seek to at least identify all of the effects that may give rise to significant externalities, even if some of these cannot be quantified in either physical or monetary terms.

In order to comply with these principles, much of the analysis described in this report looks at the effects of individual power projects, which are closely specified with respect to:

- The technologies used
- The location of the power generation plant
- The location of supporting activities
- The type of fuel used
- The source and composition of the fuel used

Each of these factors is important in determining the magnitude of impacts and hence associated externalities.

## 2.3 Defining the Boundaries of the Analysis

The starting point for fuel chain analysis is the definition of the temporal and spatial boundaries of the system under investigation, and the range of burdens and impacts to be addressed. The boundaries used in the ExternE Project are very broad. This is essential in order to ensure consistency in the application of the methodology for different fuel chains.

Certain impacts brought within these boundaries cannot be quantified at the present time, and hence the analysis is incomplete. However, this is not a problem peculiar to this style of analysis; it simply reflects the existence of gaps in available knowledge. Our rule here is that no impact that is known or suspected to exist, but cannot be quantified, should be ignored for convenience. Instead it should be retained for consideration alongside whatever analysis has been possible. Further work is needed so that unquantified effects can be better integrated into decision-making processes.

### 2.3.1 Stages of the fuel chain

For any project associated with electricity generation the system is centred on the generation plant itself. However, the system boundaries should be drawn so as to account for all potential effects of a fuel chain. The exact list of stages is clearly dependent on the fuel chain in question, but would include activities linked to the manufacture of materials for plant, construction, demolition and site restoration as well as power generation. Other stages may need to be considered, such as, exploration, extraction, processing and transport of fuel, and the generation of wastes and by-products, and their treatment prior to disposal.

In practice, a complete analysis of each stage of a fuel chain is often not necessary in order to meet the objectives of the analysis (see below). However, the onus is on the analyst to demonstrate that this is the case - it cannot simply be assumed. Worth noting is the fact that variation in laws and other local conditions will lead to major differences between the importance of different stages in different parts of the world.

A further complication arises because of the linkage between fuel chains and other activities, upstream and downstream. For example, in theory we should account for the externalities associated with (e.g.) the production of materials for the construction of the plant used to make the steel that is used to make turbines, coal wagons, etc. The benefit of doing so is, however, extremely limited. Fortunately this can be demonstrated through order-of-magnitude calculations on emissions, without the need for detailed analysis.

The treatment of waste matter and by-products deserves special mention. Impacts associated with waste sent for disposal are part of the system under analysis. However, impacts associated with waste utilised elsewhere (which are here referred to not a waste but as by-products) should be considered as part of the system to which they are transferred from the moment that they are removed from the boundaries of the fuel chain. It is of course important to be sure that a market exists for any such by-products. The capacity of, for example, the building industry to utilise gypsum from flue gas desulphurisation systems is clearly finite. If it is probable that markets for particular by-products are already saturated, the 'by-product' must be considered as waste instead. A further difficulty lies in the uncertainties about future management of waste storage sites. For example, if solid residues from a power plant are disposed in a well engineered and managed landfill there is no impact (other than land use) as long as the landfill is correctly managed; however, for the more distant future such management is not certain.

### 2.3.2 Location of fuel chain activities

One of the distinguishing features of the ExternE study is the inclusion of site dependence. For each stage of each fuel chain we have therefore identified specific locations for the power plant and all of the other activities drawn within the system boundaries. In some cases this has gone so far as to identify routes for the transport of fuel to power stations. The reason for defining our analysis to this level of detail is simply that location is important in determining the size of impacts. There are several elements to this, the most important of which are:

- Variation in technology arising from differing legal requirements (e.g. concerning the use of pollution abatement techniques, occupational safety standards, etc.);
- Variation in fuel quality;
- Variations in atmospheric dispersion;
- Differences in the sensitivity of the human and natural environment upon which fuel chain burdens impact.

The alternative to this would be to describe a 'representative' site for each activity. It was agreed at an early stage of the study that such a concept is untenable. Also, recent developments elsewhere, such as use of critical loads analysis in the revision of the Sulphur

Protocol within the United Nations Economic Commission for Europe's (UN ECE) Convention on Long Range Transboundary Air Pollution, demonstrate the importance attached to site dependence by decision makers.

However, the selection of a particular series of sites for a particular fuel chain is not altogether realistic, particularly in relation to upstream impacts. For example, although some coal fired power stations use coal from the local area, an increasing number use coal imported from a number of different countries. This has now been taken into account.

### 2.3.3 Identification of fuel chain technologies

The main objective of this project was to quantify the external costs of power generation technologies built in the 1990s. For the most part it was not concerned with future technologies that are as yet unavailable, nor with older technologies which are gradually being decommissioned.

Over recent years an increasingly prescriptive approach has been taken to the regulation of new power projects. The concept of Best Available Techniques (BAT), coupled with emission limits and environmental quality standards defined by both national and international legislation, restrict the range of alternative plant designs and rates of emission. This has made it relatively easy to select technologies for each fuel chain on a basis that is consistent across fuel chains. However, care is still needed to ensure that a particular set of assumptions is valid for any given country. Across the broader ExternE National Implementation Project particular variation has for example been found with respect to the control of $NO_x$ in different EU Member States.

As stated above, the present report deals mainly with closely specified technology options. Results have also been aggregated for the whole electricity-generating sector, providing first estimates of damages at the national level.

### 2.3.4 Identification of fuel chain burdens

For the purposes of this project the term 'burden' relates to anything that is, or could be, capable of causing an impact of whatever type. The following broad categories of 'burden' have been identified:

- Solid wastes
- Liquid wastes
- Gaseous and particulate air pollutants
- Risk of accidents
- Occupational exposure to hazardous substances
- Noise
- Others (e.g. exposure to electro-magnetic fields, emissions of heat)

During the identification of burdens no account has been taken of the likelihood of any particular burden actually causing an impact, whether serious or not. For example, in spite of the concern that has been voiced in recent years there is no definitive evidence that exposure to electro-magnetic fields associated with the transmission of electricity is capable of causing harm. The purpose of the exercise is simply to catalogue everything to provide a basis for the analysis of different fuel chains to be conducted in a consistent and transparent manner. To provide a firm basis for revision of the analysis as more information on the effects of different burdens becomes available in the future.

The need to describe burdens comprehensively is highlighted by the fact that it is only recently that the effects of long range transport of acidic pollutants, and the release of CFCs and other greenhouse gases have been appreciated. Ecosystem acidification, global warming and depletion of the ozone layer are now regarded as among the most important environmental concerns facing the world. The possibility of other apparently innocuous burdens causing risks to health and the environment should not be ignored.

### 2.3.5 Identification of impacts

The next part of the work involves identification of the potential impacts of these burdens. At this stage it is irrelevant whether a given burden will actually cause an appreciable impact; all potential impacts of the identified burdens should be reported. The emphasis here is on making analysts demonstrate that certain impacts are of little or no concern, according to current knowledge. The conclusion that the externalities associated with a particular burden or impact, when normalised to fuel chain output, are likely to be negligible is an important result that should not be passed over without comment. It will not inevitably follow that action to reduce the burden is unnecessary, as the impacts associated with it may have a serious effect on a small number of people. From a policy perspective it might imply, however, that the use of fiscal instruments might not be appropriate for dealing with the burden efficiently.

The first series of ExternE reports *(CEC, 1995a-f)* provided comprehensive listings of burdens and impacts for most of the fuel chains considered. The tasks outlined in this section and the previous one are therefore not as onerous as they seem, and will become easier with the development of appropriate databases.

### 2.3.6 Valuation criteria

Many receptors that may be affected by fuel chain activities are valued in a number of different ways. For example, forests are valued not just for the timber that they produce, but also for providing recreational resources, habitats for wildlife, their interactions (direct and indirect) with climate and the hydrological cycle, protection of buildings and people in areas subject to avalanche, etc. Externalities analysis should include all such aspects in its valuation. Again, the fact that a full quantitative valuation along these lines is rarely possible is besides the point when seeking to define what a study should seek to address: the analyst has the responsibility of gathering information on behalf of decision makers and should not make arbitrary decisions as to what may be worthy of further debate.

### 2.3.7 Spatial limits of the impact analysis

The system boundary also has spatial and temporal dimensions. Both should be designed to capture impacts as fully as possible.

This has major implications for the analysis of the effects of air pollution in particular. It necessitates extension of the analysis to a distance of hundreds of kilometres for many air pollutants operating at the 'regional' scale, such as ozone, secondary particles, and $SO_2$. For greenhouse gases the appropriate range for the analysis is obviously global. Consideration of these ranges is in marked contrast to the standard procedure employed in environmental impact assessment, which considers pollutant transport over a distance of only a few kilometres and is further restricted to primary pollutants. The importance of this issue in externalities analysis is that in many cases in the ExternE Project it has been found that regional effects of air pollutants like $SO_2$, $NO_x$ and associated secondary pollutants are far greater than effects on the local scale (for examples see CEC, 1995c). In some locations, for example close to large cities, this pattern is reversed, and accordingly the framework for assessing air pollution effects developed within the EcoSense model allows specific account to be taken of local range dispersion.

It is frequently necessary to truncate the analysis at some point, because of limits on the availability of data. Under these circumstances it is recommended that an estimate be provided of the extent to which the analysis has been restricted. For example, one could quantify the proportion of emissions of a given pollutant that have been accounted for, and the proportion left unaccounted.

### 2.3.8 Temporal limits of the impact analysis

In keeping with the previous section, impacts should be assessed over their full time course. This clearly introduces a good deal of uncertainty for long term impacts, such as those of global warming or high level radioactive waste disposal, as it requires a view to be taken on the structure of future society. There are a number of facets to this, such as global population and economic growth, technological developments, the sustainability of fossil fuel consumption and the sensitivity of the climate system to anthropogenic emissions.

The approach adopted here is that discounting should only be applied after costs are quantified. The application of any discount rate above zero can reduce the cost of major events in the distant future to a negligible figure. This perhaps brings into question the logic of a simplistic approach to discounting over time scales running far beyond the experience of recorded history. There is clear conflict here between some of the concepts that underlie traditional economic analysis and ideas on sustainability over timescales that are meaningful in the context of the history of the planet. For further information, the discounting of global warming damages is discussed further in Appendix V.

The assessment of future costs is of course not simply a discounting issue. A scenario based approach is also necessary in some cases in order to describe the possible range of outcomes. This is illustrated by the following examples;

- A richer world would be better placed to take action against the impacts of global warming than a poorer one;
- The damages attributable to the nuclear fuel chain could be greatly reduced if more effective treatments for cancer are discovered.

Despite the uncertainties involved it is informative to conduct analysis of impacts that take effect over periods of many years. By doing so it is at least possible to gain some idea of how important these effects might be in comparison to effects experienced over shorter time scales. The chief methodological and ethical issues that need to be addressed can also be identified. To ignore them would suggest that they are unlikely to be of any importance.

## 2.4 Analysis of Impact Pathways

Having identified the range of burdens and impacts that result from a fuel chain, and defined the technologies under investigation, the analysis typically proceeds as follows:

- Prioritisation of impacts
- Description of priority impact pathways
- Quantification of burdens
- Description of the receiving environment
- Quantification of impacts
- Economic valuation
- Description of uncertainties

### 2.4.1 Prioritisation of impacts

It is possible to produce a list of several hundred burdens and impacts for many fuel chains (see CEC, 1995c, pp. 49-58). A comprehensive analysis of all of these is clearly beyond the scope of externality analysis. In the context of this study, it is important to be sure that the analysis covers those effects that (according to present knowledge) will provide the greatest externalities (see the discussion on life cycle analysis in section 2.1). Accordingly, the analysis presented here is limited, though only after due consideration of the potential magnitude of all impacts that were identified for the fuel chains that were assessed. It is necessary to ask whether the decision to assess only a selection of impacts in detail reduces the value of the project as a whole. We believe that it does not, as it can be shown that many impacts (particularly those operating locally around any given fuel chain activity) will be negligible compared to the overall damages associated with the technology under examination.

There are good reasons for believing that local impacts will tend to be of less importance than regional and global effects. The first is that they tend to affect only a small number of people. Even though it is possible that some individuals may suffer very significant damages these will not amount to a significant effect when normalised against a fuel chain output in the order of several Tera-Watt ($10^{12}$ Watt) hours per year. It is likely that the most appropriate means of controlling such effects is through local planning systems, which be better able than policy developed using externalities analysis to deal flexibly with the wide range of concerns that may exist locally. A second reason for believing that local impacts will tend to be less significant is that it is typically easier to ascribe cause and effect for impacts effective over a short range than for those that operate at longer ranges. Accordingly there is a longer history of legislation to combat local effects. It is only in recent years that the international dimension of pollution of the atmosphere and water systems has been realised, and action has started to be taken to deal with them.

There are obvious exceptions to the assertion that in many cases local impacts are of less importance than others;

- Within OECD states one of the most important exceptions concerns occupational disease, and accidents that affect workers and members of the public. Given the high value attached to human life and well-being there is clear potential for associated externalities to be large.
- Other cases mainly concern renewable technologies, at least in countries in which there is a substantial body of environmental legislation governing the design and siting of nuclear and fossil-fired plant. For example, most concern over the development of wind farms typically relates to visual intrusion in natural landscapes and to noise emissions.
- There is the possibility that a set of conditions - meteorology, geography, plant design, proximity of major centres of population, etc. - can combine to create local air quality problems.

The analysis of certain upstream impacts appears to create difficulties for the consistency of the analysis. For example, if we treat emissions of $SO_2$ from a power station as a priority burden, why not include emissions of $SO_2$ from other parts of the fuel chain, for example from the production of the steel and concrete required for the construction of the power plant? Calculations made in the early stages of ExternE using databases, such as GEMIS *(Fritsche et* al, 1992), showed that the emissions associated with material inputs to fossil power plants are 2 or 3 orders of magnitude lower than those from the power generation stage. It is thus logical to expect that the impacts of such emissions are trivial in comparison, and can safely be excluded from the analysis - if they were to be included the quantified effects would be secondary to the uncertainties of the analysis of the main source of emissions. However, this does not hold across all fuel chains. In the reports on both the wind fuel chain *(CEC, 1995f)* and the photovoltaics fuel chain *(ISET, 1995),* for example, it was found that emissions associated with the manufacture of plant are capable of causing significant externalities, relative to the others that were quantified.

The selection of priorities partly depends on whether one wants to evaluate damages or externalities. In quite a few cases the externalities are small in spite of significant damages. For example, if a power plant has been in place for a long time, much of the externality associated with visual and noise impacts will have been internalised through adjustments in the price of housing. It has been argued that occupational health effects are also likely to be internalised. For example, if coal miners are rational and well informed their work contracts should offer benefits that internalise the incremental risk that they are exposed to. However, this is a very controversial assumption, as it depends precisely upon people being both rational and well informed and also upon the existence of perfect mobility in labour markets. For the present time we have quantified occupational health effects in full, leaving the assessment of the degree to which they are internalised to a later date.

It is again stressed that it would be wrong to assume that those impacts given low priority in this study are always of so little value from the perspective of energy planning that it is never worth considering them in the assessment of external costs. Each case has to be assessed individually. Differences in the local human and natural environment, and legislation need to be considered.

### 2.4.2 Description of priority impact pathways

Some impact pathways analysed in the present study are extremely simple in form. For example, the construction of a wind farm will affect the appearance of a landscape, leading to a change in visual amenity. In other cases the link between 'burden' (defined here simply as something that causes an 'impact') and monetary cost is far more complex. To clearly define the linkages involved in such cases we have drawn a series of diagrams. One of these is shown in Figure 2.2, illustrating the series of processes that need to be accounted for from emission of acidifying pollutants to valuation of impacts on agricultural crops. It is clearly far more complex than the pathway suggested by Figure 2.1.

A number of points should be made about Figure 2.2. It (and others like it) does not show what has been carried out within the project. Instead they illustrate an ideal - what one would like to do if there was no constraint on data availability. They can thus be used both in the development of the methodology and also as a check once analysis has been completed, to gain an impression of the extent to which the full externality has been quantified. This last point is important because much of the analysis presented in this report is incomplete. This reflects on the current state of knowledge of the impacts addressed. The analysis can easily be extended once further data becomes available. Also, for legibility, numerous feedbacks and interactions are not explicitly shown in the diagrammatic representation of the pathway.

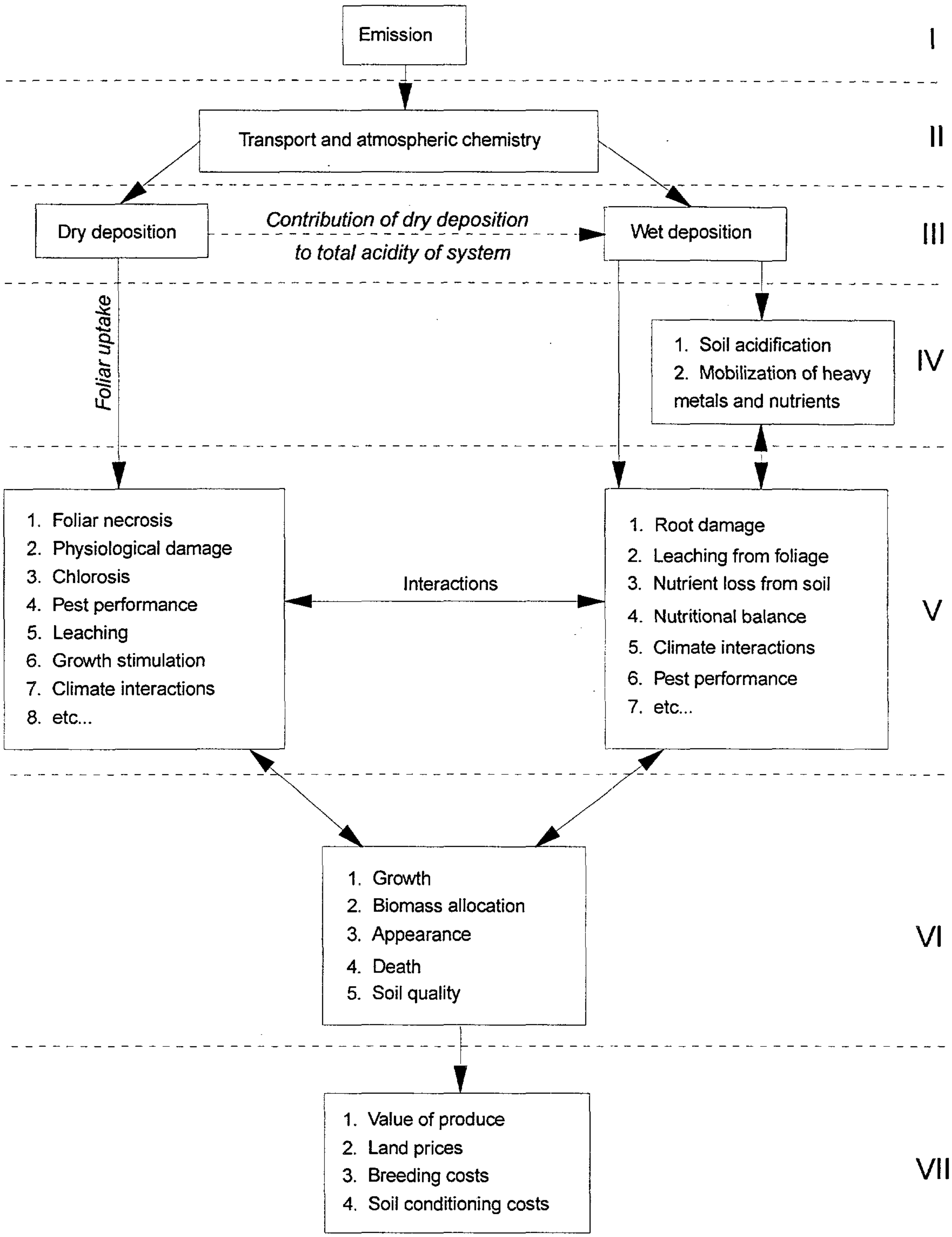


**Figure 2.2** The impact pathway showing the series of linkages between emission of acidifying pollutants and ozone precursors and valuation of impacts on agricultural systems.

### 2.4.3 Quantification of burdens

The data used to quantify burdens must be both *current* and *relevant* to the situation under analysis. Emission standards, regulation of safety in the workplace and other factors vary significantly over time and between and within different countries. It is true that the need to meet these demands creates difficulties for data collection. However, given that the objective of this work is to provide as far as possible an accurate account of the environmental and social burdens imposed by energy supply and use, these issues should not be ignored. It is notable that data for new technologies can change rapidly following their introduction. In addition to the inevitable refinement of technologies over time, manufacturers of novel equipment may be cautious in their assessment of plant performance. As an example of this latter point, $NO_x$ emission factors for combined cycle gas turbine plant currently coming on stream in several countries are far lower than was suggested by Environmental Statements written for the same plant less than five years ago.

All impacts associated with pollution of some kind require the quantification of emissions. Emission rates of the 'classical' air pollutants ($CO_2$, $SO_2$, $NO_x$, CO, volatile organic compounds and particulate matter) are quite well known. Especially well determined is the rate of $CO_2$ emission for fuel using equipment; it depends only on the efficiency of the equipment and the carbon/hydrogen ratio of the fuel - uncertainty is negligible. Emissions of the other classical air pollutants are somewhat less certain, particularly as they can vary with operating conditions, and maintenance routines. The sulphur content of different grades of oil and coal can vary by an order of magnitude, and hence, likewise, will emissions unless this is compensated for through varying the performance of abatement technologies. The general assumption made in this study is that unless otherwise specified, the technology used is the best available according to the regulations in the country of implementation, and that performance will not degrade. We have sought to limit the uncertainty associated with emissions of these pollutants by close identification of the source and quality of fuel inputs within the study.

The situation is less clear with respect to trace pollutants such as lead and mercury, since the content of these in fuel can vary by much more than an order of magnitude. Furthermore, some of these pollutants are emitted in such small quantities that even their measurement is difficult. The dirtier the fuel, the greater the uncertainty in the emission estimate. There is also the need to account for emissions to more than one media, as pollutants may be passed to air, water or land. The last category is the subject of major uncertainty, as waste has historically been sent for disposal to facilities of varying quality, ranging from simple holes in the ground to well-engineered landfills. Increasing regulation relating to the disposal of material and management of landfills should reduce uncertainty in this area greatly for analysis within the European Union, particularly given the concept of self-sufficiency enshrined in Regulation 259/93 on the supervision and control of shipments of waste into, out of and within the European Community. The same will not apply in many other parts of the world.

The problem becomes more difficult for the upstream and downstream stages of the fuel chain because of the variety of technologies that may be involved. Particularly important may be some stages of fuel chains such as biomass, where the fuel chain is potentially so diverse that it is possible that certain activities are escaping stringent environmental regulation.

The burdens discussed so far relate only to routine emissions. Burdens resulting from accidents also need to be considered. These might result in emissions (e.g. of oil) or an incremental increase in the risk of injury or death to workers or members of the public. Either way it is normally necessary to rely upon historical data to quantify accident rates. Clearly the data should be as recent as possible so that the rates used reflect current risks. Major uncertainty however is bound to be present when extreme events need to be considered, such as the disasters at Chernobyl and on the Piper Alpha oil rig in the North Sea. To some extent it is to be expected that accident rates will fall over time, drawing on experience gained. However, structural changes in industries, for example through privatisation or a decrease in union representation, may reverse such a trend.

Wherever possible data should be relevant to the country where a particular fuel chain activity takes place. Major differences in burdens may arise due to different standards covering occupational health, extension of the distance over which fuel needs to be transported, etc.

### 2.4.4 Description of the receiving environment

The use of the impact pathway approach requires a detailed definition of the scenario under analysis with respect to both time and space. This includes:

- Meteorological conditions affecting dispersion and chemistry of atmospheric pollutants
- Location, age and health of human populations relative to the source of emissions
- The status of ecological resources
- The value systems of individuals

The range of the reference environment for any impact requires expert assessment of the area influenced by the burden under investigation. As stated above, arbitrary truncation of the reference environment is methodologically wrong and will produce results that are incorrect. It is to be avoided as far as possible.

Clearly the need to describe the sensitivity of the receiving environment over a vast area (extending to the whole planet for some impacts) creates a major demand on the analyst. The large scale of the present study - which has been able to draw on data held in many different countries, simplifies this. Further to this it has been possible to draw on numerous databases that are being compiled as part of other work, for example on critical loads mapping. Databases covering the whole of Europe, describing the distribution of the key receptors affected by $SO_2$, $NO_x$, $NH_3$ and fine particles have been derived or obtained for use in the EcoSense software developed by the study team.

In order to take account of future damages, some assumption is required on the evolution of the stock at risk. In a few cases it is reasonable to assume that conditions will remain roughly constant, and that direct extrapolation from the present day is as good an approximation as any. In other cases, involving for example the emission of acidifying gases or the atmospheric concentration of greenhouse gases this assumption is untenable, and scenarios need to be developed. Confidence in these scenarios clearly declines as they extend further into the future.

### 2.4.5 Quantification of impacts

The methods used to quantify various types of impact are discussed in depth in the report on the study methodology *(European Commission, 1998)*. The functions and other data that we have used are summarised at the back of this report in Appendices I (describing the EcoSense software), II (health), III (materials), IV (ecological receptors), V (global warming effects) and VI (other impacts), VII (economic issues) and VIII (uncertainty). The complexity of the analysis varies greatly between impacts. In some cases externalities can be calculated by multiplying together as few as 3 or 4 parameters. In others it is necessary to use a series of sophisticated models linked to large databases.

Common to all of the analysis conducted on the impacts of pollutants emitted from fuel chains is the need for modelling the dispersion of pollutants and the use of a dose-response function of some kind. Again, there is much variation in the complexity of the models used (see Appendix I). The most important pollutant transport models used within ExternE relate to the atmospheric dispersion of pollutants. They need to account not only for the physical transport of pollutants by the winds but also for chemical transformation. The dispersion of pollutants that are in effect chemically stable in the region of the emission can be predicted using Gaussian plume models. These models assume source emissions are carried in a straight line by the wind, mixing with the surrounding air both horizontally and vertically to produce pollutant concentrations with a normal (or Gaussian) spatial distribution. The use of these models is typically constrained to within a distance of 100 km of the source.

Air-borne pollutant transport of course extends over much greater distances than 100 km. A different approach is needed for assessing regional transport, as chemical reactions in the atmosphere become increasingly important. This is particularly so for the acidifying pollutants. For this analysis we have used receptor-orientated Lagrangian trajectory models. The outputs from the trajectory models include atmospheric concentrations and deposition of both the emitted species and secondary pollutants formed in the atmosphere.

A major problem has so far been the lack of a regional model of ozone formation and transport within fossil-fuel power station plumes that is applicable to the European situation. In consequence a simplified approach has been adopted for assessment of ozone effects *(European Commission, 1998)*.

The term 'dose-response' is used somewhat loosely in much of this work, as what we are really talking about is the response to a given *exposure* of a pollutant in terms of atmospheric concentration, rather than an ingested *dose*. Hence the terms 'dose-response' and 'exposure-response' should be considered interchangeable. A major issue with the application of such functions concerns the assumption that they are transferable from one context to another. For example, some of the functions for health effects of air pollutants are still derived from studies in the USA. Is it valid to assume that these can be used in Europe? The answer to this question is to a certain degree unknown - there is good reason to suspect that there will be some variation, resulting from the affluence of the affected population, the exact composition of the cocktail of pollutants that the study group was exposed to, etc. Indeed, such variation has been noted in the results of different epidemiological studies. However, in most cases the view of our experts has been that transference of functions is to be preferred to ignoring particular types of impact altogether - neither option is free from uncertainty.

Dose-response functions come in a variety of functional forms, some of which are illustrated in Figure 2.3. They may be linear or non-linear and contain thresholds (e.g. critical loads) or not. Those describing effects of various air pollutants on agriculture have proved to be particularly complex, incorporating both positive and negative effects, because of the potential for certain pollutants, e.g. those containing sulphur and nitrogen, to act as fertilisers.

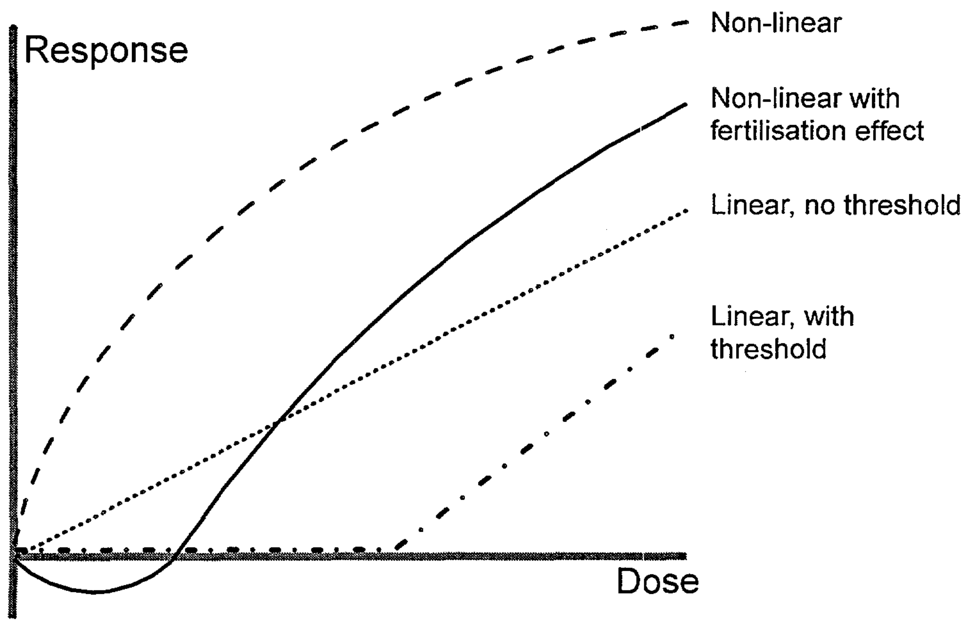


**Figure 2.3** A variety of possible forms for dose-response functions.

Ideally these functions and other models are derived from studies that are epidemiological - assessing the effects of pollutants on real populations of people, crops, etc. This type of work has the advantage of studying response under realistic conditions. However, results are much more difficult to interpret than when working under laboratory conditions, where the environment can be closely controlled. Although laboratory studies provide invaluable data on response mechanisms, they often suffer from the need to expose study populations to extremely high levels of pollutants, often significantly greater than they would be exposed to in the field. Extrapolation to lower, more realistic levels may introduce significant uncertainties, particularly in cases where there is reason to suspect that a threshold may exist.

The description and implementation of exposure-response relationships is fundamental to the entire ExternE Project. Much of the report on methodology *(European Commission, 1998)* is, accordingly, devoted to assessment of the availability and reliability of these functions.

### 2.4.6 Economic valuation

The rationale and procedures underlying the economic valuation applied within the ExternE Project are discussed in Appendix VII and in more detail in the methodology report *(European Commission, 1998)*. The approach followed is based on the quantification of individual 'willingness to pay' (WTP) for environmental benefit.

A limited number of goods of interest to this study - crops, timber, building materials, etc. - are directly marketed, and for these valuation data are easy to obtain. However, many of the more important goods of concern are not directly marketed, including human health, ecological systems and non-timber benefits of forests. Alternative techniques have been developed for valuation of such goods, the main ones being hedonic pricing, travel cost methods and contingent valuation (Appendix VII). All of these techniques involve uncertainties, though they have been considerably refined over the years.

The base year for the valuation described in this report is 1995, and all values are referenced to that year. The unit of currency used is the ECU. The exchange rate was approximately 1 ECU to US$1.25 in 1995.

The central discount rate used for the study is 3%, with upper and lower rates of 0% and 10% also used to show sensitivity to discount rate. The rationale for the selection of this range and best estimate, and a broader description of issues relating to discounting, was given in an earlier report *(CEC, 1995b)*.

### 2.4.7 Assessment of uncertainty

Uncertainty in externality estimates arises in several ways, including:

- The variability inherent in any set of data
- Extrapolation of data from the laboratory to the field
- Extrapolation of exposure-response data from one geographical location to another
- Assumptions regarding threshold conditions
- Lack of detailed information with respect to human behaviour and tastes
- Political and ethical issues, such as the selection of discount rate
- The need to assume some scenario of the future for any long term impacts
- The fact that some types of damage cannot be quantified at all

It is important to note that some of the most important uncertainties listed here are not associated with technical or scientific issues, instead they relate to political and ethical issues, and questions relating to the development of world society. It is also worth noting that, in general, the largest uncertainties are those associated with impact assessment and valuation, rather than quantification of emissions and other burdens.

Traditional statistical techniques would ideally be used to describe the uncertainties associated with each of our estimates, to enable us to report a median estimate of damage with an associated probability distribution. Unfortunately this is rarely possible without excluding some significant aspect of error, or without making some bold assumption about the shape of the probability distribution. Alternative methods are therefore required, such as sensitivity analysis, expert judgement and decision analysis. In this phase of the study a more clearly quantified description of uncertainty has been attempted than previously. Further discussion is provided in Appendix VIII, though it is worth mentioning that in this area of work uncertainties tend to be so large that additive confidence intervals usually do not make sense; instead one should specify multiplicative confidence intervals. The uncertainties of each stage of an impact pathway need to be assessed and associated errors quantified. The individual deviations for each stage are then combined to give an overall indication of confidence limits for the impact under investigation.

## 2.5 Priority Impacts Assessed in the ExternE Project

### 2.5.1 Fossil technologies

The following list of priority impacts was derived for the fossil fuel chains considered in the earlier phases of ExternE. It is necessary to repeat that this list is compiled for the specific fuel chains considered by the present study, and should be reassessed for any new cases. The first group of impacts is common to all fossil fuel chains:

1. Effects of atmospheric pollution on human health
2. Accidents affecting workers and/or the public
3. Effects of atmospheric pollution on materials
4. Effects of atmospheric pollution on crops
5. Effects of atmospheric pollution on forests
6. Effects of atmospheric pollution on freshwater fisheries
7. Effects of atmospheric pollution on unmanaged ecosystems
8. Impacts of global warming
9. Impacts of noise

To these can be added a number of impacts that are fuel chain dependent:

10. Impacts of coal and lignite mining on ground and surface waters
11. Impacts of coal mining on building and construction
12. Resettlement necessary through lignite extraction
13. Effects of accidental oil spills on marine life
14. Effects of routine emissions from exploration, development and extraction from oil and gas wells

### 2.5.2 Nuclear technologies

The priority impacts of the nuclear fuel chain to the general public are radiological and non-radiological health impacts due to routine and accidental releases to the environment. The source of these impacts is the releases of materials through atmospheric, liquid and solid waste pathways.

Occupational health impacts, from both radiological and non-radiological causes, were the next priority. These are mostly due to work accidents and radiation exposures. In most cases, statistics were used for the facility or type of technology in question. When this was not possible, estimations were taken from similar type of work or extrapolated from existing information.

Impacts on the environment of increased levels of natural background radiation due to the routine releases of radionuclides have not been considered as a priority impact pathway, except partially in the analysis of major accidental releases.

### 2.5.3 Renewable technologies

The priority impacts for renewables vary considerably from case to case. Each case is dependent upon the local conditions around the implementation of each fuel chain. For the wind fuel chain *(CEC, 1995f)* the following were considered:

1. Accidents affecting the public and/or workers
2. Effects on visual amenity
3. Effects of noise emissions on amenity
4. Effects of atmospheric emissions related to the manufacture of turbines and construction and servicing of the site

Whilst for the hydro fuel chain *(European Commission, 1995f)* another group was considered:

1. Occupational health effects
2. Employment benefits and local economic effects
3. Impacts of transmission lines on bird populations
4. Damages to private goods (forestry, agriculture, water supply, ferry traffic)
5. Damages to environmental goods and cultural objects

### 2.5.4 Related issues

It is necessary to ask whether the study fulfils its objective of consistency between fuel chains, when some impacts common to a number of fuel chains have only been considered in a select number of cases. In part this is due to the level of impact to be expected in each case - if the impact is likely to be large it should be considered in the externality assessment. If it is likely to be small it may be legitimate to ignore it, depending on the objectives of the analysis. In general we have sought to quantify the largest impacts because these are the ones that are likely to be of most relevance to questions to which external costs assessment is appropriate.

## 2.6 Summary

This Chapter has introduced the 'impact pathway' methodology of the ExternE Project. The authors believe that it provides the most appropriate way of quantifying externalities because it enables the use of the latest scientific and economic data.

Critical to the analysis is the definition of fuel chain boundaries, relating not only to the different stages considered for each fuel chain, but also to the:

- Location of each stage
- Technologies selected for each stage
- Identified burdens
- Identified impacts
- Valuation criteria
- Spatial and temporal limits of impacts

In order to achieve consistency it is necessary to draw very wide boundaries around the analysis. The difficulty with successfully achieving an assessment on these terms is slowly being resolved through the development of software and databases that greatly simplify the analysis.

The definition of 'system boundary' is thus broader than is typically used for LCA. This is necessary because our analysis goes into more detail with respect to the quantification and valuation of impacts. In doing so it is necessary to pay attention to the site of emission sources and the technologies used. We are also considering a wider range of burdens than is typical of LCA work, including, for example, occupational health effects and noise.

The analysis requires the use of numerous models and databases, allowing a logical path to be followed through the impact pathways. The functions and other data originally used by ExternE were described in an earlier report *(CEC, 1995b)*. In the present phase of the study this information has been reassessed and many aspects of it have been updated (see European Commission, 1998). It is to be anticipated that further methodological changes will be needed in the future, as further information becomes available particularly regarding the health effects of air pollution and global warming impacts, which together provide some of the most serious impacts quantified under the study.

# 3. THE NATURAL GAS FUEL CYCLE

## 3.1 Technology description

The technology analysed for this fuel cycle is a combined cycle CHP plant. The power plant has an electricity capacity of 77 MW and a heat capacity of 75 MJ/s.

The natural gas fuel chain for Denmark is shown in Figure 3.1.

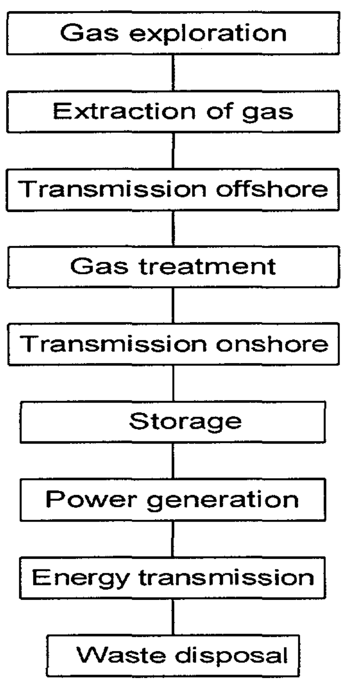


**Figure 3.1** The natural gas fuel chain for Denmark

### 3.1.1 The natural gas fuel cycle

The natural gas is explored in the North Sea. When an extraction site has been chosen, the production platform is constructed and established. After extraction, the natural gas is transmitted to the shore in pipelines to a centre for treatment and cleaning of natural gas at Esbjerg on the West Coast of Jutland. After treatment the natural gas is transmitted in pipelines onshore via large underground stores to the power generation plant. After power generation at the plant the produced energy is transmitted to the consumers. Through the whole fuel cycle different kinds of waste disposals are produced.

All natural gas utilised for energy production in Denmark is extracted in the Danish part of the North Sea, 300 km west of Esbjerg. The Danish part of the underground in the North Sea was not explored for oil until 1972 *(Ministry of Energy, 1981)*. The exploration was conducted by the Danish Underground Consortium (DUC), which also is the company extracting and producing oil and gas in the North Sea today. DUC is a consortium supported by Mærsk Sealines and Shell.

### *Gas exploration*

The exploration of natural gas was initiated in 1984. The annual production has since risen to $5x10^9$ $m^3$ by 1995. The Danish fields in the North Sea are expected to produce around $7x10^9$ $m^3$ of natural gas annually until 2005.

First, seismic explorations are used to detect formations, which might be suitable for gas extraction. Afterwards, appraisal testing is performed to check the possible productivity and composition of the gas. The seismic investigations are carried out by ship. There are three kinds of drillings. The exploration drilling is carried out either by a drill ship, semi-submersible drilling unit or jackup rig. The second drilling is the appraisal drilling, drilled for a detailed mapping of the reservoir. Drilling mud is used to control hydrostatic pressure within the borehole. The gas produced under the testing of the wells is disposed of. The last drilling is the production well.

### *Extraction of gas*

The extracted oil, gas and water are separated at the platform. Flaring of gas is installed as a safety precaution on all production platforms. The flaring depressurises the oil and gas processing facilities. If there is no market for the gas produced with the oil production, it will be flared. There are many different types of production platforms, but all of them are produced onshore. They are supported on the seabed with either steel or concrete substructures. The top facilities for drilling, production and utility systems are made of steel. Energy used for the extraction is supplied on board, normally by diesel generators.

### *Transmission offshore and gas treatment*

The gas rises from the ground by its own pressure. It is pressurised, condensed and depressurised to 140 bar and dried by triethylenglycole, which is regenerated. Afterwards, the gas is transmitted to Esbjerg in pipelines where it is expanded to 80 bar. *(Styregruppen for Forsyningskataloget, 1988)*.

The pipelines are constructed onshore. The pipes are waterproofed with bitumen and coated with steel-reinforced concrete to make sure they remain stable on the seabed. The pipes are then welded and dropped gently to the seabed. The pipelines are normally buried to protect the pipeline. Some anti-corrosion chemicals, biocides and cleaning chemicals are added to the water when the pipeline is pressure tested.

There are some releases of water vapour and heavier hydrocarbon vapours from the reservoir when natural gas is extracted. The water and the heavier hydrocarbons may condense during transmission and block the pipeline. Therefore, methanol is continuously injected near the well-head for prevention. Furthermore, an inhibitor is injected to prevent corrosion in the carbon steel pipeline and fittings. A collecting device is sent through the pipeline regularly for cleaning.

Natural gas predominantly contains methane (91%). The composition of the gas is shown in Table 3.1. Natural gas also contains ethane, heavier alkanes, nitrogen, carbon dioxide, traces of hydrogen sulphide and some water. The carbon content can, however, vary up to 20% in some drilling wells in the North Sea. Hydrogen sulphide can be removed onshore before the gas is dried, but presently the concentration of hydrogen sulphide is so low that it is not purified. Additives such as methanol are recovered and heavier hydrocarbons are removed.

**Table 3.1** Composition of natural gas from the Danish part of the North Sea *(DGC, 1993)*

| Component | Symbol | % |
|---|---|---|
| Methane | $CH_4$ | 91 |
| Ethane | $C_2H_6$ | 5.1 |
| Propane | $C_3H_8$ | 1.8 |
| Butane | $C_4H_{10}$ | 0.9 |
| Pentane | $C_{5+}$ | 0.3 |
| Nitrogen | $N_2$ | 0.32 |
| Carbon dioxide | $CO_2$ | 0.61 |
| Hydrogen sulphide | $H_2S$ | 1 |

### *Transmission onshore*

The natural gas is transmitted onshore in buried steel pipelines. The gas is delivered to the regional natural gas companies via regulation stations, where the pressure is regulated to 16 or 40 bars, and tetrehydrotiophen is added.

The natural gas used as fuel in the decentralised plant at Hillerød is delivered by The Natural Gas of the Metropolitan Region I/S and Danish Natural Gas I/S. The yearly consumption of natural gas in Denmark is $3.3 \times 10^9$ $Nm^3$. The consumption at the plant is approximately $78 \times 10^6$ $Nm^3$ *(SK Energi, 1994)* or 2.4% of the total natural gas consumption in Denmark.

### *Storage*

In Denmark two storage sites are developed. A planned extension of the sites will give a capacity of $400 \times 10^6$ $m^3$ in Lille Thorup in Jutland and $300 \times 10^6$ $m^3$ in Stenlille in Sealand. In Lille Thorup natural gas is stored in several caverns in a salt dome, while Stenlille is aquifer storage. There are plans for another storage capacity of $500 \times 10^6$ $m^3$, but the site is not yet decided *(Ministry of Environment and Energy, 1995).* The storage capacity is necessary because the natural gas is produced regularly throughout the year in the North Sea, whereas the consumption is 5 times higher in winter than in summer. Furthermore, unreliability in supply of the natural gas due to leaks in pipe etc. will be covered by the storage.

***Power generation***

Energy is produced at the combined heat and power plant in Hillerød. The plant has an electricity capacity of 77 MW with an electricity production of about 300 GWh/year. The plant has a heat capacity of 75 MJ/s, corresponding to a heat production of 370 GWh/year *(SK Energi, 1994).*

***Electricity and heat transmission***

The electricity is transmitted via a 50-kV connection from the CHP plant to the transmission system at Sealand and further on to the consumers. The district heating is transported through a heat transmission system at a length of 31 km to 7 municipal district heating systems.

***Waste disposal***

Throughout the entire natural gas fuel cycle different kinds of waste disposal are produced. The main types of solid and liquid waste produced by the gas fuel cycle are as follows:

- Domestic waste from the gas rig, and supply and construction vessels
- Oily wastes from supply and construction vessels
- Operational waste from construction activities
- Drilling fluids
- Material displaced by entrenchment of pipelines
- Materials from decommissioning of the plant

### 3.1.2 The CHP plant

The CHP plant in Hillerød produces electricity to the transmission system at Sealand and heat to 7 municipal district heating systems in the municipalities Hillerød, Farum and Værløse. The plant was started in 1991 and is operated by the Kyndby plant in Jægerspris.

Hillerød CHP plant is located at a geographical latitude of 55.54 degrees and a longitude of 12.18 degrees. The plant has an electrical capacity of 77 MW. The electricity is transmitted to the transmission system at Sealand and further on to the consumers. The plant produces about 370 mill. kWh heat/year *(SK Energi, 1994).* The district heating is transported through a heat transmission system to the municipal district heating systems. A heat storage tank makes it possible to store district heating water at times with a low district heating demand, resulting in a larger flexibility in the electricity- and heat production. The heat storage capacity is 16,000 $m^3$ corresponding to a few days of consumption.

The plant has an estimated technical lifetime of 25 years.

### 3.1.3 Site description

Hillerød CHP plant is located 2.5 km south-west of Hillerød, a town with about 25,500 inhabitants, in the county of Frederiksborg. To the east of Hillerød there is a large forest. In total there is an area of wood of 21,700 ha. in the county of Frederiksborg which is16% of its total area *(Denmark Statistics, 1995).* To the northwest and northeast of Hillerød there are two large lakes with a total area of 5,690 ha. The region around Hillerød is agricultural. North of the town lies a very popular area for summer residents. The population of the county of Frederiksborg is 350,236. The environment around Hillerød is shown in Figure 3.2.


**Figure 3.2** Hillerød and the environment (1:500,000)

Hillerød CHP plant is located 27 m above sea level. 250 m from the plant lies a small village called St. Hestehave. 1.5 km from the plant can be found the village of Ny Hammersholt with 1450 inhabitants (Figure 3.3). Although there have been efforts to let the plant fit into the environments by giving the facades a smaller pitch, the plant still dominates the environment. The plant consists of a main building at 2,000 $m^2$, a 45-m high heat storage tank, a combined office- and workshop building and a regulator station for the natural gas. The height of the stack is 35 m.

The plant is located downhill very close to the main road from Slangerup to Hillerød.

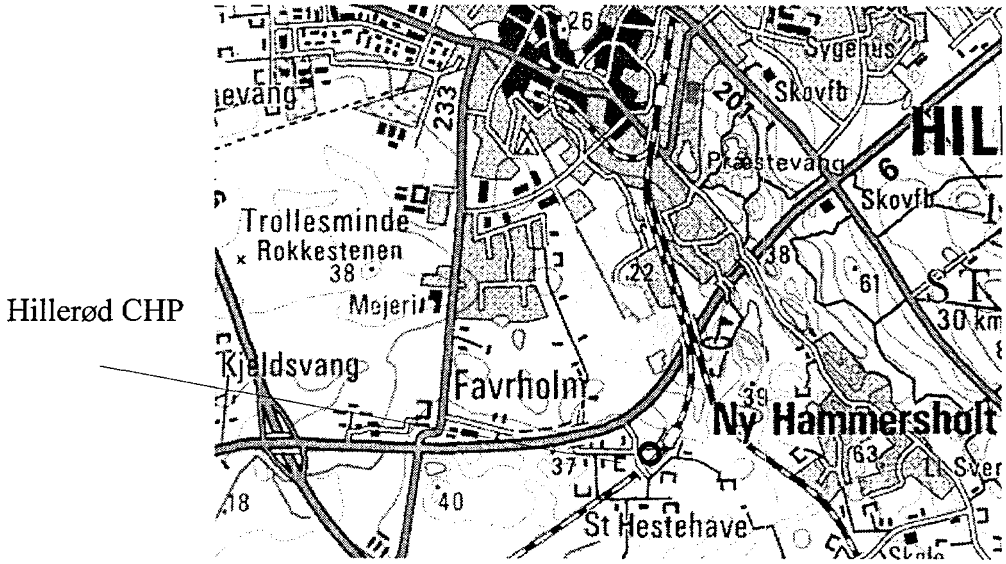


**Figure 3.3** Hillerød CHP plant and the environment (1:100,000)

## 3.2 Overview of burdens related to the natural gas fuel cycle

Burdens and impacts for the natural gas fuel cycle are divided into the following categories:

Burdens and impacts associated with

- Gas exploration
- Construction and decommissioning of gas platforms, pipelines, gas treatment facilities, power stations, waste disposal sites and transmission lines
- Operation of the gas platform
- Operation of the offshore pipeline
- Operation of the onshore pipeline
- Gas treatment and storage
- Power generation stage
- Waste disposal
- Transmission of electricity
- Transport of materials and personnel

The burdens and impacts associated with the power generation stage are divided in the following sub-categories:

- Burdens and human-related impacts
- Burdens and impacts to terrestrial ecosystems
- Burdens and impacts to aquatic ecosystems
- Burdens and impacts to non-living systems
- Burdens and human related impacts

The burdens and impacts associated with the different steps of the fuel cycle are shown in appendix IX. In the tables about 200 impacts have been identified. Only the most essential of these impacts will be considered, namely those having been given high or medium priority.

## 3.3 Selection of priority impacts

The following impacts have been identified as impacts given high priority:

- Global warming effects of greenhouse gas emissions in relation to the whole fuel cycle
- Effects of atmospheric pollution in relation to power generation and transportation
- Occupational and public accidents in relation to the whole fuel cycle
- Emissions to the marine environment in relation to the gas platforms
- Impacts specific to the physical presence of gas storage
- Visual intrusion of the CHP plant and transmission lines
- Effects of land use changes

***Global warming effects of greenhouse gas emissions in relation to the whole fuel cycle***

The construction and decommissioning of the gas platforms and transmission lines cannot be related to the specific CHP plant in Hillerød, but to the entire natural gas system in Denmark. Some rough calculations of their effects are carried out taking Hillerød's relatively small part of the gas extraction process into consideration.

In relation to power generation, $CO_2$ and other greenhouse gases are emitted to the atmosphere by natural gas combustion. Furthermore, the emission of $CO_2$ and other greenhouse gases are quantified for the extraction, flaring, transmission and distribution processes.

***Effects of atmospheric pollution in relation to power generation and transportation***

From the natural gas fuel cycle the amount of atmospheric emissions as $SO_2$, $NO_x$ and particulates are much smaller than for the coal fuel-cycle. The amount of $SO_2$ emitted during power generation is close to zero, but there are still large quantities of $NO_x$ emitted, which will cause impacts related to acidic deposition, eutrophication and formation and destruction of ozone in the troposphere. These impacts will affect human health, materials, crops, forests, freshwater fisheries and ecosystems, and have been given a high priority.

Also, in relation to transportation of people and material to the CHP plant there are emissions of $NO_x$. This has been given medium priority, but compared to the $NO_x$ emissions from the power-generation stage the amount is small and will therefore not be considered.

### *Occupational and public accidents in relation to the whole fuel cycle*

Occupational and public accidents may occur in all stages of the natural gas fuel cycle, but the accidents in the offshore phase are given an especially high priority, as these are accidents specific to the natural gas fuel-cycle. Accidents in all stages, however, will be considered.

### *Emissions to the marine environment in relation to the gas platforms*

During the construction and decommissioning of the gas platforms and transmission lines, a number of chemical substances are released into the North Sea, which may have toxic effects on marine life. The area is an important commercial fishery one and therefore the emissions to the marine environment seem rather important. On the other hand the construction and decommissioning of the gas platforms and transmission lines take place only once in a period of about 30 years, and therefore these impacts are given medium priority.

During exploration, extraction and transmission of natural gas there may be chemical emissions of minor effects. These emissions are not assessed in the study.

### *Impacts specific to the physical presence of gas storage*

In Denmark two large storage sites for natural gas are established. In one of the sites the natural gas is stored in an aquifer, while the other storage site is in salt caverns. The sites are located close to built-up areas and from the residents in the area there has been very much anxiety concerning leakage from the storage site. Another storage site is about to be established, but the residents in the area have deferred the decision about the site until now. Based on this the impacts specific to gas storage have been given high priority.

### *Visual intrusion of the CHP plant and transmission lines*

Hillerød CHP plant is located very close to a main road and is visible for quite a distance from the road. The environment around the CHP plant is open land and wood, making the plant much more dominating. Based on this the visual intrusion is given high priority.

The visual intrusion of transmission lines is not specific to natural gas and will therefore not be included in this study.

### *Effects of land use changes*

The construction of the plant and the lying of pipelines are changing the land use patterns. This may have some impact on biodiversity, either by total destruction of a habitat or by secondary effects such as changing local drainage patterns. The latter effect is the most probable for the actual CHP site. Effects of land use changes are given medium priority.

## 3.4 Quantification of impacts and damages

As Hillerød plant is a CHP plant producing heat as well as electricity, damages will have to be allocated to heat as well as electricity. The allocation of damages to heat and electricity will be based on exergy as shown in Table 3.3.

While the Carnot factor for electricity is 1, the Carnot factor of the heat flow is determined by

$$\eta_c = 1 - T_a/T$$

Where $T_a$ is the ambient temperature and T is the process temperature.

With an ambient temperature of 288 K the Carnot factor for heat production for Hillerød CHP plant is 0.23. The total annual exergy production is

10.8 E+14 J * 1 + 13.32 E+14 J *0.23 = 13.86 E+14 J

As electricity generation contributes to 78% of the annual exergy production 78% of the damages should be allocated to electricity and 22% to heat.

**Table 3.2** Allocation of damage costs to heat and electricity production

| | Electricity | Heat |
|---|---|---|
| Energy content in produced energy | 300 E+6 kWh | 370 E+6 kWh |
| Exergy in produced energy | 10.8 E+14 J | 3.06 E+14 J |
| Percent of exergy | 78% | 22% |

### 3.4.1 Global warming effects of greenhouse gas emissions in relation to power generation

Greenhouse gases are emitted at many steps of the fuel cycle: the production of platforms, leakage from various sources, emission from transportation and production of energy. Further details are available in Appendix IX.

The total emissions in $CO_2$-equivalents per kWh related to the Hillerød CHP plant is shown in Table 3.3. 78% of the emissions have been allocated to electricity production and 22% to heat production.

**Table 3.3** Total emissions in $CO_2$ equivalents per kWh related to Hillerød CHP plant

| | $CO_2$ emissions kt/year | g $CO_2$ /kWh $_{el}$ | g $CO_2$ /kWh $_{heat}$ |
|---|---|---|---|
| Exploration for gas | unknown | | |
| Well drilling | unknown | | |
| Offshore extraction | 19 | 49 | 11 |
| Flaring | 9.4 | 24 | 5.6 |
| Offshore pipeline leakage | negligible | | |
| Transport of personnel to rig | negligible | | |
| Liquid removal treatment | negligible | | |
| Onshore compression | 1.6 | 4.2 | 1.0 |
| Onshore pipeline leakage | 0.24 | 0.6 | 0.1 |
| Production, construction and transportation of platforms and power plant | 0.27 | 0.7 | 0.2 |
| Transport of personnel to power plant | negligible | | |
| Power generation | 177 | 460 | 105 |
| Total | 208 | 539 | 123 |

The table shows that the $CO_2$ emissions are predominantly derived from the power generation phase, which is not surprising. Emissions due to offshore extraction and flaring are relatively high, those due to onshore pipeline leakage and emissions from production of materials are almost negligible. Emissions from exploration and well drilling are unknown but probably small compared to the other large sources.

The monetisation values used for $CO_2$ have been estimated using the FUND and Open Framework Models (Appendix V). Four different values have been used as seen in Table 3.4.

**Table 3.4** Total damage due to global warming in mecu/kWh related to Hillerød CHP plant

| Monetary value for $CO_2$ | mECU/kWh$_{el}$ | mECU/kWh$_{heat}$ |
|---|---|---|
| 3.8 ECU/t $CO_2$ | 2.05 | 0.47 |
| 18 ECU/t $_{CO2}$ | 9.70 | 2.21 |
| 46 ECU/t $_{CO2}$ | 24.80 | 5.66 |
| 139 ECU/t $CO_2$ | 74.94 | 17.10 |

### 3.4.2 Effects of atmospheric pollution in relation to power generation

From the natural gas fuel cycle there will be emissions of $SO_2$, $NO_x$, CO and particulates, which will affect human health, materials, agriculture, forests, freshwater and ecosystems. The total emissions of $SO_2$, $NO_x$, particulates and CO from the power plant are shown in Table 3.5.

**Table 3.5** Total emissions of $SO_2$, $NO_x$, particulates and CO in mg/kWh (details in appendix IX)

| | emissions t/year | emissions mg/kWh $_{el}$ | emissions mg/kWh $_{heat}$ |
|---|---|---|---|
| $SO_2$ | 0.681 | 2.2 | 0.6 |
| $NO_x$ | 192 | 624 | 169 |
| Particulates | 0.0091 | 0.03 | 0.008 |
| CO | 45.4 | 148 | 40 |

The analysis of effects of emissions to the air is based on the EcoSense model. The emission of $SO_2$ is so small that its use in EcoSense will give incorrect results, as it is close to the background level. Therefore, the emission of $SO_2$ is set to zero in EcoSense.

The total damage in mECU/kWh related to the Hillerød CHP plant is shown for the mid estimate in Table 3.6. The damages are shown in details in Appendix IX.

**Table 3.6** Total damage in mECU/kWh related to the Hillerød CHP plant for the mid estimate

| Receptor | Pollutant | Damages related to electricity production, mECU/kWh$_{el}$ | Damages related to heat production, mECU/kWh$_{heat}$ |
|---|---|---|---|
| Crops | nitrogen, acid deposition | 52e-4 | 14e-4 |
| Human health | tsp, nitrates, $NO_x$, CO | 2.91 | 0.81 |
| Materials | wet deposition | 0.04 | 0.01 |
| | Total | 2.96 | 0.82 |

98% of the damages are related to human health. Of these 98% are caused by emissions of $NO_x$.

### *Ozone*

The damages due to ozone are calculated based on the $NO_x$ emission related to the plant. The following numbers are used for monetisation (Appendix II):

**Table 3.7** Monetisation values for ozone

| | | Monetisation value |
|---|---|---|
| Mortality | Europe | 259 ECU/t $NO_x$ |
| | Outside Europe | 153 ECU/t $NO_x$ |
| Morbidity | Europe | 460 ECU/t $NO_x$ |
| | Outside Europe | 272 ECU/t $NO_x$ |
| Crops | Europe | 200 ECU/t $NO_x$ |
| | Outside Europe | 150 ECU/t $NO_x$ |

The $NO_x$ emissions are 0.624 g/kWh$_{el}$, and 0.169 g/kWh$_{heat}$. The damages due to ozone via $NO_x$ are shown in Table 3.8.

**Table 3.8** Damages due to ozone via $NO_x$ emission

| | Hillerød (electricity) | Hillerød (heat) |
|---|---|---|
| Mortality | 0.26 mECU/kWh$_{el}$ | 0.07 mECU/kWh$_{heat}$ |
| Morbidity | 0.46 mECU/kWh$_{el}$ | 0.12 mECU/kWh$_{heat}$ |
| Crops | 0.22 mECU/kWh$_{el}$ | 0.06 mECU/kWh$_{heat}$ |
| Total | 0.94 mECU/kWh$_{el}$ | 0.25 mECU/kWh$_{heat}$ |

### 3.4.3 Occupational and public accidents in relation to the whole fuel cycle

The natural gas fuel cycle may influence both occupational and public health.

*Occupational health*

Occupational health effects occur at every stage of the natural gas fuel cycle. The total figures for offshore accidents and by construction and production of materials are shown in Table 3.9 taking the 25-year lifetime into account. Values used for monetisation are 3,100,000 ECU for fatal accidents, 94,000 ECU for major and 1,400 for minor accidents.

**Table 3.9** Accidents offshore and by construction and production of materials (details in Appendix IX)

| Process step | Total damages per year | Damages mECU/kWh$_{el}$ | Damages mECU/kWh$_{heat}$ |
|---|---|---|---|
| Offshore construction and operation | Fatal: 0.016 | 0.13 | 0.04 |
| | Major: 0.123 | 0.03 | 9e-3 |
| | Minor: 0.825 | 3e-3 | 8e-4 |
| Production of materials and technologies for the power plant | Fatal: 0.0001 | 8e-4 | 2e-4 |
| | Major: 0.010 | 2e-3 | 7e-4 |
| | Minor:0.070 | 3e-4 | 1e-4 |
| Construction of the power plant | Fatal: 0.0001 | 8e-4 | 2e-4 |
| | Major: 0.010 | 2e-3 | 7e-4 |
| | Minor:0.070 | 3e-4 | 1e-4 |
| Total | | 0.17 | 0.05 |

As seen from the table accidents related to the offshore construction and operation are dominant.

*Public health*

The dominant effects of the natural gas fuel cycle on public health arise from air pollution emitted during the plant operation. These effects are handled in the EcoSense model above. Other impacts related to the fuel cycle or impacts from injury and death caused by accidents are estimated to be much lower than the impacts related to air emissions, and will therefore not be considered.

Results for public accidents arising from increased road traffic have been calculated for both the construction and operational phases of the natural gas plant (in phase I of the ExternE project) *(CEC, 1995 a-f),* and have been found to be insignificant. These accidents will not be considered for the Danish plant.

### 3.4.4 Emissions to the marine environment

The largest sources of pollution in the North Sea are river-borne and atmospheric inputs. The priority impact from the natural gas fuel cycle to the marine environment is identified to be emissions from drilling activity and the discharge of water produced from the gas treatment plant.

Offshore oil and gas platforms do contribute to marine pollution levels, but emission levels are relatively low compared to the quantities from river-borne sewage and industrial effluents. Of the total amount of oil entering the North Sea, 10% has been estimated to arise from offshore oil and gas activity *(CEC, 1995d).* The emissions to the marine environment from the natural gas fuel cycle are, however, regarded to be negligible.

### 3.4.5 Impacts specific to gas storage

Two large storage sites for natural gas have been established in Denmark. The natural gas in one of the sites is stored in an aquifer, while the other site consists of salt caverns. The sites are located close to built-up areas and from the residents in the area there has been very much anxiety about leakage from the storage site. Another storage site is about to be established, but the residents in the area have deferred making a decision about the site until now. Based on this the impacts specific to gas storage have been given high priority.

In order to monetise the impacts related to gas storage it is assumed that the residents located at the storage area will be influenced by the storage in such a way that the prices of the houses will decrease.

The impacts related to gas storage are estimated by using the same monetisation value of the effect on house prices as for houses in the vicinity of wind turbines in clusters (chapter 5.4.2), although the damages are quite different. In the case of the wind turbines the damages are noise and visibility, while the damage related to the storage is people being afraid of living close to the storage.

Data for monetisation of impacts related to gas storage are shown in Table 3.10.

**Table 3.10** Monetisation of impacts related to gas storage

| | |
|---|---|
| Storage volume | 300 mill $Nm^3$ |
| Energy production per $Nm^3$ natural gas for Hillerød CHP plant | 8.6 kWh |
| Number of houses influenced | 200 |
| Effect on house price | 16,500 ECU |
| Monetisation of impacts related to gas storage | 1.0 $mECU/kWh_{el}$ |
| | 0.28 $mECU/kWh_{heat}$ |

The result is accompanied by a large uncertainty. As mentioned above the effect on house prices is based on prices in the vicinity of wind turbines in clusters, and the effect on prices may be different in the vicinity of a natural gas storage area.

### 3.4.6 Visual intrusion

Hillerød CHP plant is located very close to a main road and is visible for quite a distance from this road. The environment around the CHP plant is open land and wood, so that the plant especially dominates the landscape. Based on this the visual intrusion is given high priority.

The visual intrusion is quantified and monetised in the same way as the wind farm (chapter 5.4.2), where a survey of house prices has shown a systematic tendency for houses that at the purchase date are affected by wind turbines to be cheaper than other houses. The same conditions must exist for houses close to the Hillerød CHP plant. The height of the storage tank is 45 m. The wind turbines, on the other hand, are 60 m high and the radius of influence by the wind farm has been defined as 1500 meters. Based on this the radius of influence of the storage tank has been defined as 1000 m taking into account that the CHP plant is located in a smaller valley. In this radius around 25 houses are located.

The monetisation value used, 2135 ECU, is the same as that for houses that lie close to a single wind turbine. Based on these assumptions the visual intrusion of the CHP plant is monetised to 0.0025 $mECU/kWh_{el}$ and 0.0007 $mECU/kWh_{heat}$.

As for the wind turbines, the visual intrusion of the CHP plant for road users is not monetised, as this intrusion is very brief.

### 3.4.7 Effects of land use changes

The natural gas transmission system is subject to Danish conservation legislation and Danish environmental legislation. This means that, in connection with design and construction of the transmission system, special consideration must be given to the surrounding countryside (woodland, lakes, and shores) and possible historic remains (grave mounds, ruins, etc.) *(Dansk Olie & Naturgas, 1994)*. Based on these considerations the effects of land use changes are monetised to zero.

## 3.5 Interpretation of the results and sensitivity analyses

The total impacts and damages which have been assessed in relation to the Hillerød CHP plant are shown in Table 3.11.

In the table the geometric standard deviations $\sigma_g$ for each damage are shown. The labels are:
A = high confidence, corresponding to $\sigma_g = 2.5$ to 4;
B = medium confidence, corresponding to $\sigma_g = 4$ to 6;
C = low confidence, corresponding to $\sigma_g = 6$ to 12;

**Table 3.11** Damages in relation to the natural gas fuel cycle for Hillerød CHP plant

| | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ | $\sigma_g$ |
|---|---|---|---|
| **POWER GENERATION** | | | |
| Public health | | | |
| Mortality*- YOLL *(VSL)* | 2.81 (18.69) | 0.79 (5.15) | B |
| *of which TSP* | *2 e-4 (7 e-4)* | *1 e-4 (4 e-4)* | |
| *$SO_2$* | *0* | *0* | |
| *$NO_x$* | *2.55 (9.44)* | *0.72 (2.66)* | |
| *$NO_x$ (via ozone)* | *0.26 (9.25)* | *0.07 (2.49)* | |
| Morbidity | 0.82 | 0.21 | B |
| *of which TSP, $SO_2$, $NO_x$, CO* | *0.36* | *0.09* | |
| *$NO_x$ (via ozone)* | *0.46* | *0.12* | |
| Accidents | ng | ng | A |
| Occupational health | ng | ng | A |
| Crops | 0.22 | 0.06 | B |
| *of which $SO_2$* | *0* | *0* | |
| *$NO_x$ (via ozone)* | *0.22* | *0.06* | |
| Ecosystems | nq | nq | |
| Materials | 0.04 | 0.01 | B |
| Visual impacts | 25e-4 | 7e-4 | C |
| Global warming | | | C |
| low | 1.75 | 0.40 | |
| mid 3% | 8.27 | 1.89 | |
| mid 1% | 21.14 | 4.82 | |
| high | 63.88 | 14.58 | |
| **OTHER FUEL CYCLE STAGES** | | | |
| Public health | nq | nq | |
| Occupational health | 0.17 | 0.05 | A |
| Ecological effects | ng | ng | |
| Marine environment | ng | ng | |
| Land use changes | 0 | 0 | |
| Natural gas storage | 1.0 | 0.28 | C |
| Global warming | | | C |
| low | 0.30 | 0.07 | |
| mid 3% | 1.43 | 0.32 | |
| mid 1% | 3.66 | 0.84 | |
| high | 11.06 | 2.52 | |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

ng: negligible; nq: not quantified; iq: only impact quantified; - : not relevant

In Table 3.11 the mortality impacts are calculated by using the years of life lost approach. Global warming accounts for 31% of the damages for the low estimate and as much as 94%

for the upper estimate. Table 3.12 shows the total mortality damages related to the natural gas fuel cycle at Hillerød CHP plant. This includes mortality, morbidity, accidents and global warming. The damages in brackets are based on the value of statistical life approach. If this approach was used for the estimation of the total damages mortality damages would account for 96%.

**Table 3.12** Mortality damages of the natural gas fuel cycle for Hillerød CHP plant

| | | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ |
|---|---|---|---|
| YOLL *(VSL)* | low | 5.68 (21.56) | 1.48 (5.84) |
| | mid 3% | 13.33 (29.21) | 3.22 (7.58) |
| | mid 1% | 28.43 (44.31) | 6.67 (11.03) |
| | high | 78.57 (94.45) | 18.11 (22.47) |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

**Table 3.13** Damage costs for the natural gas fuel cycle for Hillerød CHP plant

| | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ | $\sigma_g$ |
|---|---|---|---|
| Power generation | 5.64-67.77 | 1.47-15.65 | A-C |
| Other fuel cycle stages | 1.47-12.23 | 0.40-2.85 | B-C |
| Subtotal | 7.11-80.00 | 1.87-18.50 | B-C |

Table 3.13 shows that about 80% of the damages from the natural gas fuel cycle for Hillerød CHP plant are related to the power generation stage. The damages are due to the emissions emitted in the power generation phase. In the mid-upper estimate 82% of the damages are related to $CO_2$ emissions, while 98% of the damages related to other emissions are due to $NO_x$. This result points out the importance of trying to reduce the emissions of $NO_x$ in the burning of natural gas. However, this has already been done to a certain extent in the case of Hillerød.

Table 3.14 shows the damage costs per pollutant.

**Table 3.14** Damages by pollutant

| | ECU / t of pollutant |
|---|---|
| $SO_2$ *- YOLL *(VSL)* | - |
| $NO_x$ *- YOLL *(VSL)* | 4,728 *(15,770)* |
| $PM_{10}$ *- YOLL *(VSL)* | 6,666 *(23,333)* |
| $NO_x$ (via ozone) | 1500 |
| $CO_2$ | 3.8-18-46-139 |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

Figure 3.4 shows the dominant damages related to the natural gas fuel cycle divided into electricity and heat. The damages due to atmospheric pollution, being mortality, morbidity and global warming, are by far the largest of the damages from the natural gas cycle using the mid-1% estimate for global warming. Also, the uncertainties concerning natural gas storage are serious, while occupational accidents only account for a minor part of the total. The damages to crops and materials are also related to $NO_x$ and $SO_2$ emissions, but as the $SO_2$ emissions from the plant are almost zero these damages are negligible in the figure.

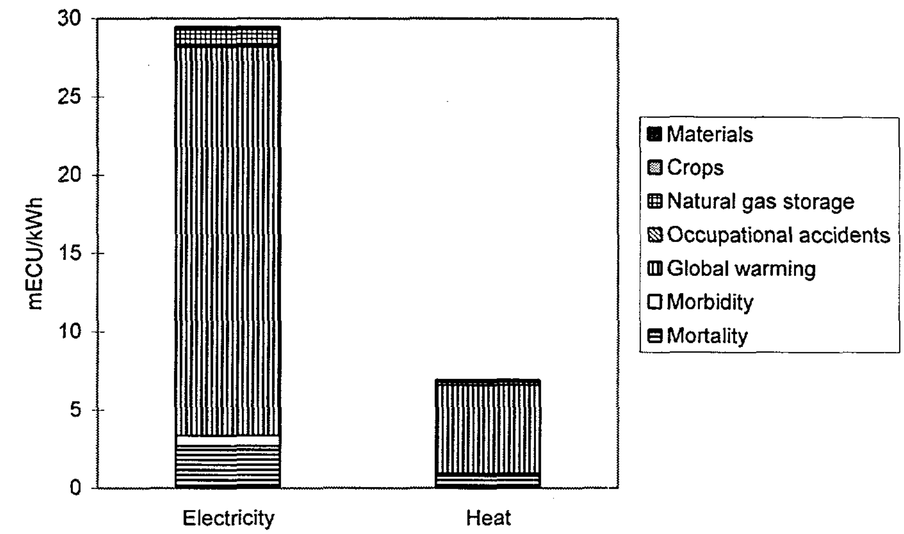


**Figure 3.4** The main damages related to the natural gas fuel cycle subdivided into electricity and heat

Figure 3.5 shows the damages related to electricity generation depending on the monetarisation value used for $CO_2$. The figure shows the importance of the $CO_2$ value chosen, as the externalities increase from about 7 in the low estimate to around 80 in the upper estimate, where global warming is totally dominating.

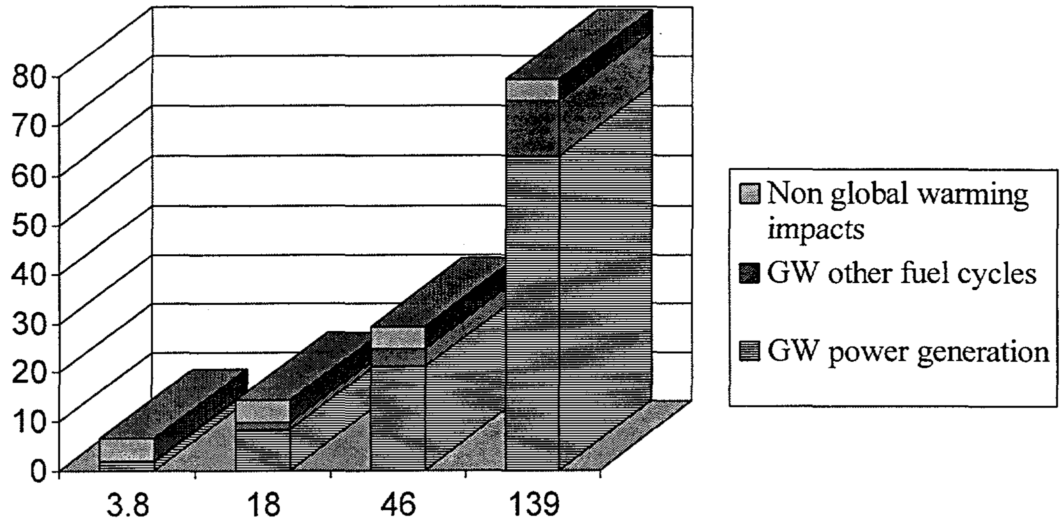


**Figure 3.5** Damages related to the natural gas fuel cycle depending on the monetisation value for global warming

# 4. THE BIOGAS FUEL CYCLE

## 4.1 Technology description

The technology analysed for this fuel cycle is a large joint biogas plant in Denmark, Ribe Biogas Plant (RBP). RBP is one of the 19 large joint biogas plants in the country and produces biogas on slurry from 79 farms. The biogas is used in Ribe-Nørremark Combined Heat and Power (R-NCHP) Plant, owned by Sønderjyllands Højspændingsværk. The power plant has an electricity capacity of 993 kW and a heat capacity of 1814 kJ/s.

### 4.1.1 The biogas fuel cycle

The slurry supplied at RBP is produced at 79 farms around Ribe. The slurry from the farms comprises 80% of all incoming biomass to RBP. Approximately 75% of the slurry stems from cattle farms and 25% from swine farms. The slurry is in most cases produced in stables without animal bedding.

The slurry is transported from the farms directly to the biogas plant in unpressurised tanks, and after digestion the digested biomass is either transported back to the farm or stored in intermediate storage facilities. Around 50% of the digested biomass is stored in the intermediate storage for some months. The radius within which the storage facilities are established is approximately 10 km.

After arrival at the plant the slurry is mixed with organic waste containing easily digestible organic matter from different food processing industries, especially abattoir wastes, fish processing waste and flotation sludge.

The biogas produced is transmitted under low pressure through an underground pipeline 2 km to the combined heat and power plant in Ribe-Nørremark where heat and electricity are produced. The heat is delivered to the local district heating system and the electricity sold to the national electricity grid. In Figure 4.1 the fuel cycle is illustrated schematically.

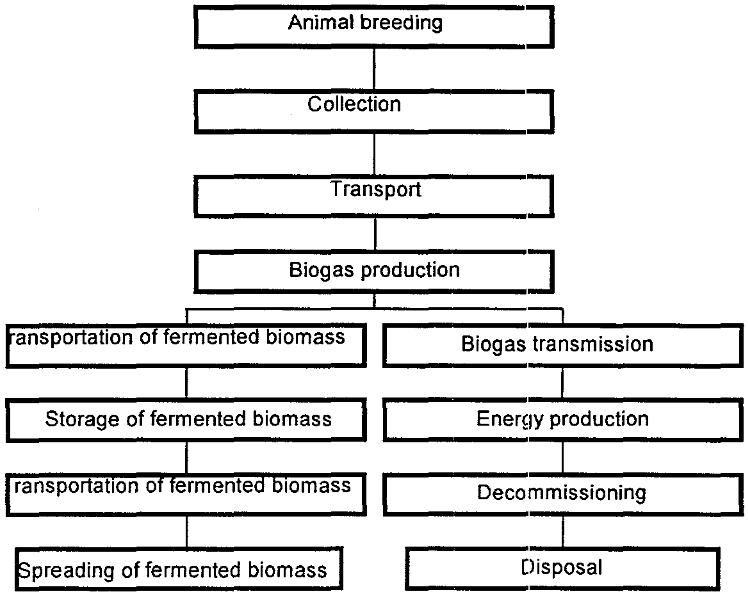


**Figure 4.1** The biogas fuel cycle

### *Collection and transportation of biomass*

The slurry is collected from a small buffer tank (approx.125 $m^3$) at the farm by trucks from RBP and then transported to the biogas plant. The unpressurised tanks are equipped with a rotor to homogenise the biomass to avoid unloading problems.

RBP uses now three trucks with unpressurised tanks. The two small trucks are 4-ale trucks with a total weight of 32 t and may be loaded with 18 t per transport. The third is a semi-trailer with a loading capacity of 28 t.

After digestion at the biogas plant the biomass is transported back to the farms or stored in intermediate storage tanks. The transportation of digested biomass is normally done in the same transportation process when collecting slurry for reducing transportation costs. This means that the trucks bring digested biomass to the farm and bring "raw" slurry back to the biogas plant. Therefore, the trucks are equipped with a washing system and the tanks are washed after each transport of raw slurry to the biogas plant. The intermediate storage tanks and the farm storage have a total capacity corresponding to nine months production of slurry (and industrial wastes). The financing of the intermediate storage is organised so that farms which do not have sufficient storage capacity at their location rent storage capacity at the intermediate storage.

The organisation of transportation of industrial organic waste is different among biogas plants, varying with the size of the plant. At RBP the semi-trailer is used to transport the industrial organic waste and, when not doing this, to transport slurry from the farms with the best loading facilities. All digested biomass is in the end transported to the farms and spread on the fields.

At RBP the transportation process has been organised with intermediate storage facilities to reduce transportation costs and obtain an optimal spreading of digested biomass among the farmers according to their biomass demand.

***Production of biogas and gas treatment***

Biogas is the product of an anaerobic biological process called methanogenesis. The process of methanogenesis is the result of four consecutive steps: 1) solubilization-hydrolysis, 2) fermentation (or acidogenesis), 3) link processes, and 4) methanogenesis *(Pauss, et al, 1987).*

Biogas contains between 50% and 80% $CH_4$, and 15% to 45% $CO_2$. In addition, it contains about 5% water and traces of hydrogen, sulphur and mercaptan. Water vapour in biogas can be removed by condensation, compression and/or cooling. The water content in the gas at RBP is almost negligible when it enters the CHP plant.

***The biogas plant***

Ribe Biogas Plant is described in chapter 4.1.2.

***Transmission of biogas and operation of pipelines***

Biogas is transmitted 2 km from Ribe Biogas Plant to Ribe Nørremark CHP Plant. The biogas is transmitted either to low-pressure gas storage (1000 Nm3) or to two compressors to condense water from the biogas, or it is flared.

***The power plant***

The power plant will be described in detail in chapter 4.1.3.

***Production, construction and decommissioning of plants and pipelines***

The biogas fuel cycle consists of two plants, the biogas plant and the CHP plant connected with a 2-km transmission line for biogas transmission. For both plants the materials used for manufacturing the plants are concrete, steel and different non-steel metals. The buildings for receiving biomass, the reactors, pipes, and engines are made of steel and other metals. Only the main building for the staff is built of concrete and bricks. All storage facilities use concrete as building material.

The CHP plant is also made up of steel and other metals except for the operating room which is constructed with bricks. The transmission lines are made of steel, and pumps and other machinery are made of different metals.

There are 3 trucks with a lifetime of 5-7 years. The lifetime of the biogas plant and the CHP plant is estimated to be 15 years.

### *Disposal of wastes*

The main "waste" at the biogas plant is the fermented biomass. In this case, this is not regarded as a waste, however, but rather as a valuable fertiliser for agriculture. Another way of looking at it is that the slurry has been "borrowed" by the biogas plant for the $CH_4$ production and is afterwards delivered back to the farms. Otherwise, there would be a significant waste problem at the biogas plant and it would probably not be interesting to produce biogas. This is, for instance, the case for industries providing the organic industrial wastes. They would not produce biogas themselves and the biogas plant is able to solve their waste problem. In this way industry gets rid of a waste problem and the farms get the benefit of using the fermented biomass as a fertiliser. Alternatively, the industrial organic wastes would be disposed of in disposal dumps.

The biogas plant produces waste only in the form of waste from maintenance and repairing of materials. The same applies to the CHP plant. When decommissioning the plants, materials which are not recycled will be disposed of in disposal dumps.

### *Storage of biomass*

The size of RBP implies that the transportation distances for the slurry are relatively high. Therefore 26 intermediate storage facilities have been established to reduce transportation costs. The slurry is collected directly at the farm, and around 50% of the fermented biomass are transported back to the farm immediately after fermentation. The other 50% are transported to the intermediate storage where it is stored for up to 9 months.

### *Transport of materials and personnel*

The transport of biomass, which is the main transportation service in the biogas fuel cycle, has been described and discussed above. Other transportation demands concern the transportation of workers from home to RBP as well as truck drivers from home to RBP when the trucks are parked at the biogas plant. Other transportation demands regard transportation of materials such as the delivery of spare parts, professional help from electricians and other technicians and delivery of diesel for the trucks.

*Spreading of biomass*

Biomass is spread on the fields as manure during the growing season in spring. Many different technologies exist for spreading the fermented biomass, depending mainly on the water content of the medium. New technologies have been developed to utilise the N-content in the manure as effectively as possible, by limiting the emission of N in the form of $NH_3$ to air and $NO_3^-$ lost by percolation. These technologies are being increasingly used. Around 50% of the manure are spread on growing crops and 50% before sawing.

*Transmission of heat and electricity*

Transmission of heat and electricity is not taken into consideration in the present study.

### 4.1.2 The biogas plant

RBP is a thermophilic plant with a biomass supply of 410 t of biomass per day. The total biogas production is around 12,000 m$^3$ per day. In 1995, the plant itself consumed 12% of the biogas production, which was used for heating the incoming biomass. Around 11,000 m$^3$ of biogas were transmitted to the Ribe-Nørremark CHP plant per day. The biogas used at the plant is burned in a gas boiler. At RBP, the biogas is stored in a low-pressure storage facility before it is transmitted to the CHP plant. The capacity of the storage tank is 1,000 m$^3$ corresponding to 2.5 hours of normal biogas production. At the biogas plant, biogas has been used for space heating, hot water and steam for heat supply/heat exchange. Today diesel is used as fuel at the biogas plant.

*Power generation (Ribe-Nørremark combined heat and power plant)*

Ribe-Nørremark CHP plant consists of a 1 $MW_{el}$ gas engine (Caterpillar) and a steam boiler of 5 MW. The original gas engine is now being exchanged with a new Jenbacker gas engine prepared for $NO_x$ cleaning, but the new engine is not presently planned to be equipped with the $NO_x$-cleaning system. The electricity is sold to the utilities and the heat is distributed through a district heating system covering Ribe-Nørremark. The district heating system will in the future be connected to the larger district heating system in Ribe. The electricity production is based on biogas alone, whereas the heat production at the plant is based on both biogas and natural gas as fuels.

### 4.1.3 Site description

Ribe Biogas Plant lies in an open field north of the town of Ribe (with a population of 7,890), and the combined heat and power plant is situated in the outskirts of the town, 2 km from the biogas plant.

The surrounding area of the biogas plant is flat with only little forestland nearby. The height above sea level is only a few meters, and there are a few small hills. The soil is sandy. Along the coast west of Ribe, there is a wetland area, which has high nature conservation priority.

This encompasses the areas between the coast and the two islands, Fanø and Mandø, but the wetlands continue down the coast, including the coastal area of Germany. 20 km north of Ribe there is the large town of Esbjerg, with a population of 72,200. The population density of Ribe county is 70.8 person/km$^2$. Ribe and its surrounding are shown in Figure 4.2.

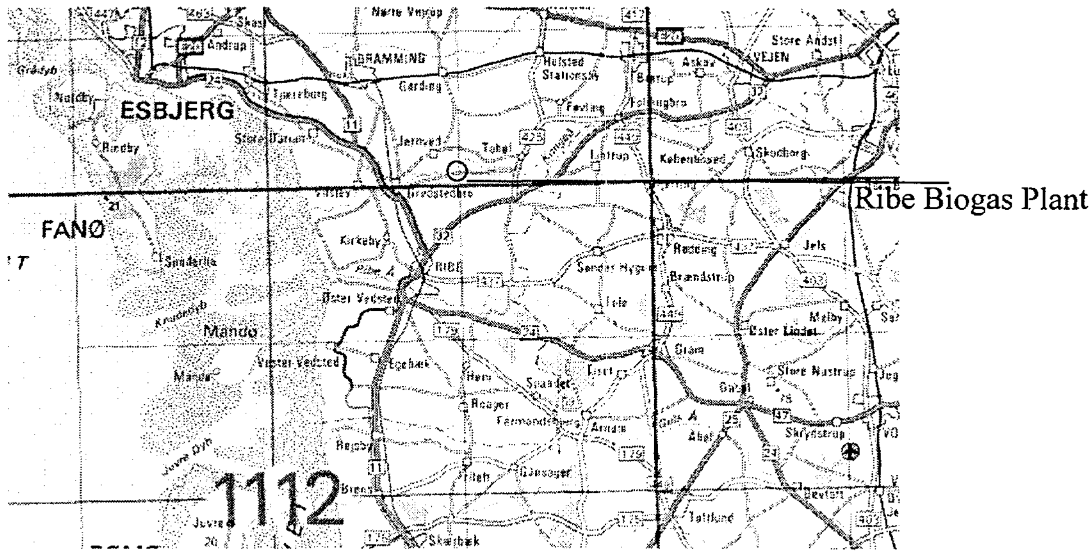


**Figure 4.2** Ribe and its surroundings (1:500,000)

The population of Fanø is 3,210 on an area of 5,580 ha and 72 live at Mandø with an area of 763 ha *(Denmark Statistics, 1995)*. Ribe County consists of 313,000 ha of which 64% is cultivated for agriculture, and 10% of the area in the council is forest/plantation. 3.6% of the area is conserved. Less than 1% of the area in Ribe County consists of lakes. A large part of the area is conserved region consisting of moors. At Fanø around 25% of the conserved area is moors.

## 4.2 Overview of burdens related to the biogas fuel cycle

The overall idea of the damage cost approach is to quantify and monetise marginal damages. This approach can also be taken in the Life Cycle Assessments method where the system boundaries define the marginal impacts. In some cases it is not important to identify the system boundaries if the fuel cycle is relatively well defined and the fuel chain is not interconnected with other economic sectors. However, in the case of using slurry for biogas production, the definition of system boundaries becomes very important, because the utilisation of agricultural wastes for energy is closely connected to activities in the agricultural sector. The question then arises how the different environmental impacts from the agricultural sector and the energy sector shall be allocated? The system boundaries are briefly described in the following section before the environmental impacts are identified and prioritised. The discussion of system boundaries will be taken up in the following sections where the identification and prioritisation of environmental impacts are given.

### 4.2.1 Definition and description of system boundaries

The fuel cycle involves a CHP power plant where heat is produced and transported in a district heating system and electricity is transmitted to the grid. It has been decided not to include the electricity grid and district heating system in the present analysis.

For the part of the fuel cycle, which involves environmental impacts interconnected with other economic sectors, the system boundaries are more difficult to establish. The utilisation of slurry for biogas production involves the agricultural sector by using animal slurry as well as the food processing sector by utilising industrial organic waste. The emission of $CH_4$ from the traditional storage of slurry in Denmark is changed and the utilisation of industrial organic wastes changes the emission of $CH_4$ from disposal dumps, where they would normally be disposed. The same kind of comparison is discussed in this chapter with regard to emissions of $NH_3$ and $H_2S$ to air and $NO_3^-$ to soil.

### 4.2.2 Identification of impacts

The biogas fuel cycle may be divided into four major groups where environmental impacts are similar. These are outlined below and summarised in the following sections:

- Collection and transportation of slurry, industrial organic waste and digested biomass (primary emissions)
- Production and transmission of biogas, storage and spreading of digested biomass (primary emissions)
- Production of electricity and heat (primary emissions)
- Production, construction and decommissioning of the biogas plant, biomass storage tanks, transmission lines and CHP plant (secondary emissions)

***Collection and transportation of slurry, industrial organic wastes and digested biomass***

Impacts due to the collection and transportation of slurry, industrial organic wastes and digested biomass are related mainly to atmospheric emissions due to fuel combustion and different impacts due to the traffic of heavy trucks. The heavy traffic affects pedestrians, cyclists and other drivers at the roads and residents on the road where the biomass is transported. The effect on occupational health is negligible. The same applies to impacts on ecosystems.

***Production of biogas, transmission of biogas and storage and spreading of digested biomass (primary emissions)***

Impacts due to production of biogas, transmission of biogas and storage and spreading of digested biomass are mainly primary emissions from handling the biomass. In the working environment only major injuries and death are prioritised for valuation. Impacts, which are prioritised, are acidification due to emissions of $NH_3$ and greenhouse effect due to emissions of $CH_4$. Impacts due to $H_2S$ emission are negligible. Emissions to soil of pathogens and $NO_3^-$ are also prioritised for further evaluation.

***Production of electricity and heat (primary emissions)***

Environmental impacts related to the production of energy with biogas are related mostly to the working environment in operation and maintenance of the CHP plant and to impacts related to the emission of pollutants to air from the combustion process. The only impacts, which are prioritised, are major injuries and deaths by operation of the power plant and damages related to the atmospheric emissions.

***Production, construction and decommissioning of the biogas plant, biomass storage tanks, transmission lines and CHP plant (secondary emissions)***

The most important environmental impacts related to production, construction and decommissioning of the biogas plant, biomass storage tanks, transmission lines and CHP plant are related to energy consumption (secondary emissions). Impacts related to the working environment are neglected and the same applies to water and soil emissions, which are also secondary emissions from the viewpoint of the biogas fuel cycle. Other burdens, which are no so important related to the biogas fuel cycle are noise, the physical presence and land uses for the biogas plant, the transmissions lines as well as the CHP. These burdens are therefore also neglected.

## 4.3 Selection of priority impacts

In Table 4.1 the burdens, receptors and impacts which are prioritised are listed. The burdens are divided into occupational health, primary and secondary emissions to air, public health and emission to soil. Also the receptors and the impacts are outlined in the table. Finally, the various parts of the fuel cycle where the impacts are identified are outlined.

**Table 4.1** Burdens and impacts prioritised for further evaluation

| Burden | Receptor | Impact | Step of fuel cycle |
|---|---|---|---|
| *Occupational health:* | | | |
| Accidents | Workers | Major injuries<br>Death | Material production<br>Production of biogas<br>Production of energy |
| *Atmospheric emissions*: | | | |
| Emissions from fuel combustion: $NO_x$, $SO_2$, $N_2O$, $CO_2$, $NH_3$ and particulates | General public<br>Crops<br>Forests<br>Materials | Health effects<br>Damage to crops<br>Damage to forests<br>Damage to materials | Production of energy<br>Production of biogas<br>Storage and spreading of biomass |
| *Atmospheric emissions*: | | | |
| Secondary emissions: $NO_x$, $SO_2$, $CO_2$ | Numerous | Numerous | Energy consumption for production of biogas plant and CHP plant |
| *Public Health*: | | | |
| Traffic | Pedestrians/cyclists /other drivers/ houses along transportation roads | Minor injuries<br>Major injuries<br>Deaths<br>Noise | Transportation |
| *Emissions to soil*: | | | |
| Percolation of pathogens | General public | Pollution of drinking water | Spreading of biomass |
| Percolation of $NO_3^-$ | General public | Pollution of drinking water | |

## 4.4 Quantification of impacts and damages

As Ribe-Nørremark plant is a CHP plant producing heat as well as electricity, damages will have to be allocated to heat as well as electricity. The allocation of damages to heat and electricity will be based on exergy as shown in Table 4.2.

While the Carnot factor for electricity is 1, the Carnot factor of the heat flow is determined by

$$\eta_c = 1 - T_a/T$$

where $T_a$ is the ambient temperature and T is the process temperature.

With an ambient temperature of 288 K the Carnot factor for heat production for Ribe-Nørremark biogas plant is 0.27. Using this Carnot factor results in that 68% of the damages should be allocated to electricity and 32% to heat (chapter 3.4).

**Table 4.2** Allocation of damage costs to heat and electricity production

| | Electricity | Heat |
|---|---|---|
| Energy content in produced energy | 6.97 E+6 kWh | 12.1 E+6 kWh |
| Exergy in produced energy (Carnot factor f. heat=0.27) | 25.1 E+14 J | 11.8 E+14 J |
| Percent of exergy | 68% | 32% |

This allocation procedure is carried out for all damages. For the results of the EcoSense model this gives some problems as the output from EcoSense is shown in damages per kWh produced. Therefore 68% of the damages of the EcoSense runs are allocated to the electricity production directly and 32% of the damages, which were allocated to the electricity production, is instead allocated to heat production.

### 4.4.1 Impacts of atmospheric emissions

Atmospheric emissions are produced in several phases of the biogas fuel cycle, and atmospheric emission is the main impact throughout the biogas fuel cycle. Emissions to air from the collection and transportation of slurry and industrial organic wastes, storage of fermented biomass, and production and transmission of biogas are quantified and monetised where possible. Furthermore, primary emissions are produced by electricity and heat production. Secondary emissions are produced and quantified in relation to the construction and decommissioning of the biogas plant, biomass tankers, transmission lines and CHP plant.

***Emissions from collection and transportation of slurry and industrial organic wastes***

Emissions from the collection and transportation of slurry and industrial waste are due to the consumption of fossil fuels. The trucks transport raw slurry from the farms to the biogas plant and transport digested biomass back to the farmers or to an intermediate storage tank. This is normally done in the same transportation process in order to reduce transportation costs. The total diesel consumption for transportation at Ribe Biogas Plant is 153 $m^3$ (1995) or 6.4 TJ per year. The fuel consumption was 1.4 km/l and the average load of the trucks 23 t per transport. The total annual emissions from transportation are listed in Table 4.3.

**Table 4.3** Atmospheric emissions due to transportation of biomass

| | $CO_2$ | $SO_2$ | NOx | PM10 |
|---|---|---|---|---|
| Total emissions (kg/year) | 475,000 | 604 | 6290 | 340 |
| Emissions in $g/kWh_{el}$ | 50.8 | 0.064 | 0.672 | 0.036 |
| Emissions in $g/kWh_{heat}$ | 14.3 | 0.018 | 0.190 | 0.010 |

Damages due to $CO_2$ emission are calculated later in the total $CO_2$ balance of the biogas fuel cycle (Table 4.9). Damages due to $SO_2$ and $NO_x$ emissions from transportation are monetised for the regional damages only, using EcoSense. Damages found in the local model in EcoSense are considerably underestimated because the model are build for calculating damages from emissions from large power plants and high stacks. The regional model, however, which is based on the chemical transitions of $SO_2$ and $NO_x$, is used giving an order of magnitude of the damages due to emissions from transportation. The regional damages of $SO_2$ and $NO_x$ emissions in this connection are probably overestimated as it in EcoSense is assumed that the pollutants are emitted from the stack of RBP (50m). The emission from the transportation is calculated using the same flue gas volume and the same full load hours as for combustion of biogas.

The total damage calculated in EcoSense from the transportation process caused by atmospheric emission is shown in Table 4.4.

**Table 4.4** Total damage from atmospheric emissions from transportation (mECU/kWh).

| Receptor | Damage mECU/kWh$_{el}$ | Damage mECU/kWh$_{heat}$ |
|---|---|---|
| Crops | 16*e-4 | 4*e-4 |
| Materials | 0.05 | 0.01 |
| Human health | 3.57 | 1.00 |
| Total | 3.62 | 1.01 |

***Emissions from storage of fermented biomass***

In the present study it is assumed that 10% of the easily digestible amount of C in the biomass sources would be converted into $CH_4$ in traditional storage of the biomass. This emission would be produced either in the storage tanks at the farms or from the organic waste disposed at disposal dumps. This means that if the C in the non-fermented slurry and industrial organic waste is converted into $CH_4$ at a biogas plant and the biogas combusted for energy purposes, this would reduce the corresponding $CH_4$ emission from the agricultural sector and disposal dumps by 10%. In some studies this conversion factor has been regarded to be somewhat higher *(Tafdrup, 1995) (Fenhann, Kilde, 1994).*

***Emissions from production and transmission of biogas***

At Ribe Biogas Plant the different tanks are equipped with a lid primarily to avoid $NH_3$ emission. The $CH_4$ production in the buffer tanks is relatively low, as the biomass here still is at ambient temperature. Therefore, the $CH_4$ production in these tanks occurs mainly during summer. The largest part of the $CH_4$ is of course produced in the reactors. After leaving the reactor the fermented biomass is stored for some days before it is brought either directly to the farms or to intermediate storage tanks.

Below the avoided emissions of $CH_4$ are summarised, excluding $CH_4$ emissions from transportation and combustion. The emission of $CH_4$ after spreading the fermented biomass on the fields is regarded to be negligible as the fermented biomass dries almost instantly. Furthermore, all C-sources suitable for anaerobic digestion is digested for production of $CH_4$ and $CO_2$. The remaining C-sources are lignoses and celluloses suitable for making the soil fertile. The total $CO_2$ balance of the biogas fuel cycle is shown in Table 4.9.

**Table 4.5** Emission of $CH_4$ through the biogas fuel cycle
($CH_4$ emission from transportation and combustion is not included)

| | kg $CH_4$/year | g $CH_4/kWh_{el}$ | g $CH_4/kWh_{heat}$ |
|---|---|---|---|
| Normal storage (up to 9 months) | 145,000 | 15.3 | 4.3 |
| Leakage, biogas plant | 35,000 | 3.8 | 1.1 |
| Total avoided emissions | 110,000 | 11.5 | 3.2 |

### *Emissions from power generation*

During power generation there will be a large amount of different emissions. In this case the emissions of $SO_2$, $NO_x$ and $CH_4$ are of main interest in affecting human health, materials, agriculture, forests, freshwater and ecosystems. None of these emissions, however, are measured directly at the Ribe Nørremark CHP plant. Generic values for gas engines are used for $NO_x$, CH4, and $SO_2$ emissions determined from the $H_2S$ content in the gas. The emission of $CH_4$ is due to passage of unburned gas through the gas engine. This unburned amount is measured to be 1.8% for engines of size 0.5-1 MW. For engines in the range of 1-2 MW the amount passing through is 2.5% *(DGC, 1996)*. In this case 1.8% is used, which means that 703 t of $CO_2$ pass through the gas engine, taking into account that the $CO_2$ content in biogas is only 64% compared with 91% in natural gas. The figures are shown in Table 4.6.

**Table 4.6** Total annual emission from combustion

| | $CO_2$-eq | SO2 | $NO_x$ | PM10 |
|---|---|---|---|---|
| Total emission in kg/year | 703,000 | 720 | 13,200 | 0.14 |
| Emission in $g/kWh_{el}$ | 75.1 | 0.075 | 1.35 | 1.5 e-5 |
| Emission in $g/kWh_{heat}$ | 21.0 | 0.021 | 0.35 | 4.1 e-6 |

The emissions of $SO_2$ and $NO_x$ have been used as input data in the EcoSense model. The total damage from the power generation process caused by atmospheric emissions calculated in EcoSense is shown in Table 4.7.

**Table 4.7** Total damages from atmospheric emissions from power generation in mECU/kWh

| Receptor | Damage $mECU/kWh_{el}$ | Damage $mECU/kWh_{heat}$ |
|---|---|---|
| Crops | 25*e-4 | 16*e-4 |
| Materials | 0.06 | 0.01 |
| Human health | 7.40 | 2.13 |
| Total | 7.46 | 2.14 |

### *Emission of nitrousoxide ($N_2O$)*

The emissions of $N_2O$ result mainly from denitrification when slurry is spread on the fields. How much of the N in the fermented as well as non-fermented biomass, which is converted into $N_2O$, depends on the soil, the N-content in the slurry, the pH value, emission of $NH_3$ and the amount of N in organic form. Changes of emissions of $N_2O$ are assumed to be negligible compared to the normal handling of the slurry, and the damage related to emissions of $N_2O$ is therefore regarded to be negligible. $N_2O$ is quantified only in relation to the combustion process.

### *Emission of ammonia ($NH_3$)*

The emission of $NH_3$ occurs when the slurry is exposed to air. Thus emission occur at the initial storage at the farm in the 9 months storage, as well as at the intermediate storage facilities and when the biomass is spread on the fields as manure. The emission depends on the content of $NH_4^+$ in the slurry, the pH value and other factors. How much of the N from $NH_4^+$ that evaporates also depends on the method used to spread the slurry and which kind of crops is cultivated.

It has not been possible to obtain exact figures for the total N-content in the raw slurry coming into the Ribe Biogas Plant. But the N-content in the outgoing biomass is known. At the biogas plant it is estimated that 3-5% of the total N is lost in the form of $NH_3$ at the storage tanks. The figure depends, however, on the actual pH value. At normal storage tanks at farms the evaporation of $NH_3$ reaches 20-22% of total N during storage due to the different pH value.

The loss of $NH_3$ is also high during spreading. In the case where the slurry is spread directly on the soil and harrowed into the soil, the emission is negligible. But in the case where it is spread on the soil in the traditional way the emission of $NH_3$ is significant.

There are, however, so many different parameters, both positive and negative, involved in quantifying emissions of $NH_3^+$, that it has been decided not to quantify the emission of $NH_3$ in the present study assuming that the impact will be negligible. A detailed study will have to be site-specific.

### *Emission of hydrogensulfide ($H_2S$)*

The unpleasant odours from biogas plants are due mostly to $H_2S$ emission. Looking at emission of S the emission of $H_2S$ is negligible compared with that of $SO_2$ from combustion processes. Also the odour problems are small. At the modern biogas plant in Ribe the odour is almost non-existent and the biogas plant is established far from houses.

The intermediate storage tanks are normally not established close to houses. Compared to the normal storage tank on the farm, the odour problems are reduced considerably, because the normal storage tanks are situated close to the farm. In both cases, the release of unpleasant odours occurs at the initial storage tank on the farm.

Disturbing odours also appear when the slurry is spread on the fields. In this case it is normally assumed that the problem arising from spreading fermented slurry is less compared to the problem that appears when raw slurry is spread.

By summing up, the odours will be somewhat less serious for the fermented slurry, but it will not be quantified, and the problem is regarded to be negligible.

***Emissions to soil***

Emissions to soil are primarily a result of spreading fermented and non-fermented biomass. In other parts of the life cycle process this emission is neglected.

***Emission of Nitrate ($NO_3^-$)***

Regulations have been established in Denmark for spreading Nitrogen both organic and inorganic. This means, for example, that slurry must not be spread from May to February, with few exceptions. Pollution of groundwater is the main reason to reduce leaching of $NO_3^-$. It is important to consider how N is applied to the fields. When organic N is applied to growing plants they have longer absorption times due to the required denitrification process.

In general terms, the amount of organic N in fermented slurry is lower than in non-fermented slurry. To a large extent N is in the form of $NH_4^+$ in fermented slurry, which increases the emissions of $NH_3$. It does not seem to increase the leaching of $NO_3^-$, but increase the uptake of inorganic N, both $NH_3$ and $NO_3^-$ between 5% and 15% compared to untreated slurry.

The risk of percolation of $NO_3^-$ with subsequent pollution of drinking water also depends on the solid composition of the soil. In soils with a high content of clay (as in Zealand) the risk of percolation is limited, whereas soils in West Jutland are more sandy and the risk for polluting drinking water with $NO_3^-$ is therefore higher. Ribe is situated in an area with sandy soils. However, as for emissions of $NH_3$ there are positive and negative impacts and it has not been possible to define a specific value. The damages are estimated to be negligible, or lower than using especially traditionally cow manure.

***Total emissions of $SO_2$ and $NO_x$***

The total emission of $SO_2$ and $NO_x$ is shown in Table 4.8. Damages have been determined for the emissions from transportation and combustion with EcoSense. As the emission from production not is well defined (between electricity and heat production) it is not possible to calculate the damages with EcoSense. They are only included to show its order of magnitude compared with the emissions from transportation and combustion. As seen the emission of $NO_x$ and $SO_2$ from production of technologies is around one-tenth of that from the transportation and combustion processes combined. The damages are therefore estimated to be around one-tenth of the damages from the transportation and combustion processes. However, these damages are not included in the final figures.

**Table 4.8** Total emission of $NO_x$ and $SO_2$ throughout the biogas fuel cycle

| | $SO_2$ | $NO_x$ |
|---|---|---|
| Transportation (kg/year) | 604 | 6,290 |
| Combustion (kg/year) | 720 | 13,200 |
| Production of technologies (kg/year) | 1,400 | 1010 |
| Total emissions (kg/year) | 2,700 | 20,500 |

***Total emission of greenhouse gases***

The total emission of greenhouse gases is shown in Table 4.9. Emissions are allocated between electricity and heat. Positive values show damages whereas negative values show benefits. The largest source of $CO_2$ emission is leakage in relation to the biogas production at the biogas plant. The second largest is $CH_4$, which passes through the engine unburned. The third largest is emission of $CO_2$ from fuel combustion in the transportation process and the fourth emissions due to production of the biogas plant. The benefit of avoiding emission of $CH_4$ in the normal storage tanks is, however, greater than the total emission from the various production processes. The $CO_2$ balance hence ends up with a benefit in the $CO_2$ budget of 86 grams of $CO_2$-equivalents per $kWh_{el}$.

**Table 4.9** Total $CO_2$ balance of the biogas fuel cycle
(a minus sign indicates avoided emissions)

| Emission g/kWh | Greenhouse gas | Emission in g $CO_2$-equivalents/$kWh_{el}$ | Emission in g $CO_2$-equivalents/$kWh_{heat}$ |
|---|---|---|---|
| Production of technologies | various | +26 | +7.4 |
| Transportation | various | +51 | +14 |
| Combustion | various | +3.9 | +1.1 |
| Combustion | $CH_4$ | +75 | +21 |
| *Sub total* | *all* | *+156* | *+44* |
| Storage tanks at farms (avoided) | $CH_4$ | -322 | -91 |
| Leakage at biogas plant | $CH_4$ | +81 | +23 |
| *Subtotal* | *$CH_4$* | *-241* | *-68* |
| Total | all | -86 | -24 |

The monetisation values used for $CO_2$ have been estimated using the FUND and Open Framework Models (Appendix V). Four different values have been used as seen in Table 4.10.

**Table 4.10** Total avoided damage due to global warming in mecu/kWh related to Ribe-Nørremark biogas plant

| Monetary value for $CO_2$ | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ |
|---|---|---|
| 3.8 ECU/t $CO_2$ | 0.33 | 0.09 |
| 18 ECU/t $CO_2$ | 1.57 | 0.43 |
| 46 ECU/t $CO_2$ | 4.0 | 1.10 |
| 139 ECU/t $CO_2$ | 12.09 | 3.34 |

### *Ozone*

The damages due to ozone is calculated based on the $NO_x$ emission related to the plant. The following numbers are used for monetisation (See Appendix II):

**Table 4.11** Monetisation values for ozone

| | | Monetisation value |
|---|---|---|
| Mortality | Europe | 259 ECU/t $NO_x$ |
| | Outside Europe | 153 ECU/t $NO_x$ |
| Morbidity | Europe | 460 ECU/t $NO_x$ |
| | Outside Europe | 272 ECU/t $NO_x$ |
| Crops | Europe | 200 ECU/t $NO_x$ |
| | Outside Europe | 150 ECU/t $NO_x$ |

The $NO_x$ emissions related to transportation, combustion and production of technologies are assumed to have impacts only within Europe. The $NO_x$ emissions from combustion are

1.41 $g/kWh_{el}$, and 0.40 $g/kWh_{heat}$ and from transportation 0.67 $g/kWh_{el}$, and 0.19 $g/kWh_{heat}$. The damages due to ozone via $NO_x$ are shown in Table 4.12.

**Table 4.12** Damages due to ozone via $NO_x$ emission

| | RBP (electricity) | RBP (heat) |
|---|---|---|
| Mortality | 0.86 $mECU/kWh_{el}$ | 0.24 $mECU/kWh_{heat}$ |
| Morbidity | 1.52 $mECU/kWh_{el}$ | 0.43 $mECU/kWh_{heat}$ |
| Crops | 0.73 $mECU/kWh_{el}$ | 0.21 $mECU/kWh_{heat}$ |
| Total | 3.11 $mECU/kWh_{el}$ | 0.88 $mECU/kWh_{heat}$ |

### *Road damage*

The intermediate storage tanks are situated in average at a distance of approximately 10 km from the biogas plant. An equation for calculating damage costs is suggested by Linares, 1997:

N*KM*MC/VPD, where

N: Number of truck passages (per year)
KM: Number of km travelled on that road
MC: Maintenance costs for that type of road (ordinary conservation costs, such as cleaning, signals, etc. have not been included)
VPD: Design number of truck passages for that road type.

In Denmark it is reasonable to subtract 50% of the costs as a result of the weather. Furthermore, it is assumed that only 50% of the costs are related to road repair and therefore directly related to the truck transport. Using the above-mentioned values and assuming that only local county roads are used for transporting slurry, and regional county roads are used for transporting the organic waste, the damage costs will be 0.61 mECU per $kWh_{el}$ and 0.17 $mECU/kWh_{heat}$.

### *Accidents in the working environment*

Materials used for the biogas plant are estimated to weigh 2,500 t. With an average rate of accidents of 50 per million working hours and 50 hours of work per tonne the total number of accidents is 6.25 for producing the biogas plant. The total damage is shown in Table 4.13 indicating the damages allocated to both electricity and heat. The differentiation between accidents involving deaths, major and minor accidents follows the figures for the engineering sector in UK *(CEC, 1995d)*.

**Table 4.13** Damages due to accidents in production of materials and technologies for the biogas plant

| | Killed | Serious injuries | Minor injuries | Total damages |
|---|---|---|---|---|
| Production of biogas plant | 0.010 | 0.81 | 5.44 | |
| Value | 3.1 MECU | 94,000 ECU | 1,400 ECU | |
| Damage $mECU/kWh_{el}$ | 0.22 | 0.54 | 54 e-3 | 0.82 |
| Damage $mECU/kWh_{heat}$ | 62 e-3 | 0.15 | 15 e-3 | 0.23 |

### *Road accidents*

The accidents can be subdivided into public accidents and those in the working environment. Public accidents are connected to accidents in traffic as well as working accidents from the biogas plant and the transportation of manure.

For public accidents the following accident data are estimated from statistical information over the years 1990-1994 *(Automobil-importørernes sammenslutning, 1995) (Denmark Statistics, 1995):*

- Accidents per million km transportation : 0.15
- Killed per million km of transportation: 0.009

Using these figures and a total transportation of 246,000 km pr. year the number of accidents and deaths in relation to transportation of employees and transportation of biomass at the biogas plant in its 15-year lifetime will be 0.028 killed and 0.56 accidents. In Table 4.14 the accidents are divided into minor and major ones assuming that 40% are minor damages and 55% major damages. The last 5% involve killed persons. The total damages are 0.83 $mECU/kWh_{el}$ and 0.23 $mECU/kWh_{heat}$ after allocation between electricity and heat.

**Table 4.14** Accidents due to public transportation

| | Killed | Serious injuries | Minor injuries | Total damages |
|---|---|---|---|---|
| Accidents | 0.028 | 0.31 | 0.25 | |
| Value per accident | 3.1 MECU | 94,000 ECU | 1,400 ECU | |
| Damage $mECU/kWh_{el}$ | 0.62 | 0.21 | 25 e-4 | 0.83 |
| Damage $mECU/kWh_{heat}$ | 0.18 | 59 e-3 | 71 e-5 | 0.23 |

## 4.5 Interpretation of the results and sensitivity analyses

In the following tables the total damage from the biogas fuel cycle is shown. The largest damage is due to impacts on human health from emission of $NO_x$, $SO_2$ and to some extent TSP. The road damages are second, producing almost the same damage as the impact from the combustion process on human health. Other significant contributions come from damages due to public road accidents as well as accidents in the working environment due to production of the materials and technologies.

**Table 4.15** Damages in relation to the biogas fuel cycle for Ribe Biogas Plant (power generation)

| | mECU/$kWh_{el}$ | mECU/$kWh_{heat}$ | $\sigma_g$ |
|---|---|---|---|
| **POWER GENERATION** | | | |
| Public health | | | |
| Mortality*- YOLL *(VSL)* | 7.15 (49.12) | 2.05 (13.89) | B |
| *of which TSP* | *6 e-5 (3 e-4)* | *2 e-5 (9 e-5)* | |
| *$SO_2$* | *0.18 (0.78)* | *0.06 (0.26)* | |
| *$NO_x$* | *6.39 (27.71)* | *1.83 (7.94)* | |
| *$NO_x$ (via ozone)* | *0.58 (20.63)* | *0.16 (5.69)* | |
| Morbidity | 1.86 | 0.53 | B |
| *of which TSP, $SO_2$, $NO_x$* | *0.83* | *0.24* | |
| *$NO_x$ (via ozone)* | *1.03* | *0.29* | |
| Accidents | ng | ng | A |
| Crops | 0.49 | 0.14 | B |
| *of which $SO_2$* | *25 e-4* | *16 e-4* | |
| *$NO_x$ (via ozone)* | *0.49* | *0.14* | |
| Ecosystems | ng | ng | |
| Materials | 0.06 | 0.01 | B |
| Emission to soil | ng | ng | |
| Land use changes | ng | ng | |
| Global warming | | | C |
| low | 0.30 | 0.17 | |
| mid 3% | 1.42 | 0.81 | |
| mid 1% | 3.63 | 2.06 | |
| high | 10.97 | 6.22 | |

In the table the geometric standard deviations $\sigma_g$ for each damage are shown. The labels are:

A = high confidence, corresponding to $\sigma_g$ = 2.5 to 4;

B = medium confidence, corresponding to $\sigma_g$ = 4 to 6;

C = low confidence, corresponding to $\sigma_g$ = 6 to 12;

**Table 4.16** Damages in relation to the biogas fuel cycle for Ribe Biogas Plant (other fuel cycles)

| | mECU/kWh$_{el}$ | mECU/kWh$_{heat}$ | $\sigma_g$ |
|---|---|---|---|
| **OTHER FUEL CYCLE STAGES** | | | |
| **Transportation of biomass** | | | |
| Public health | | | |
| Mortality*- YOLL *(VSL)* | 3.45 (23.70) | 0.97 (6.71) | B |
| *of which TSP* | *2 e-3 (9 e-3)* | *5 e-4 (2 e-3)* | |
| *$SO_2$* | *0.19 (0.82)* | *0.05 (0.22)* | |
| *$NO_x$* | *2.98 (12.92)* | *0.84 (3.64)* | |
| *$NO_x$ (via ozone)* | *0.28 (9.96)* | *0.08 (2.85)* | |
| Morbidity | 0.89 | 0.25 | B |
| *of which TSP, $SO_2$, $NO_x$* | *0.40* | *0.11* | |
| *$NO_x$ (via ozone)* | *0.49* | *0.14* | |
| Accidents | 0.83 | 0.23 | A |
| Occupational health | 0.82 | 0.23 | A |
| Crops | 0.24 | 0.07 | B |
| *of which $SO_2$* | *16 e-4* | *4 e-4* | |
| *$NO_x$ (via ozone)* | *0.24* | *0.07* | |
| Materials | 0.05 | 0.01 | B |
| Road damage | 0.61 | 0.17 | |
| Global warming | | | C |
| low | -0.63 | -0.26 | |
| mid 3% | -2.99 | -1.24 | |
| mid 1% | -7.63 | -3.16 | |
| high | -23.06 | -9.56 | |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

ng: negligible; nq: not quantified; iq: only impact quantified; - : not relevant

In Table 4.15 and Table 4.16 the mortality impacts are calculated by using the years of life lost approach. Table 4.17 shows the total mortality damages related to the biogas fuel cycle at Ribe-Nørremark. This includes mortality, morbidity, accidents and global warming. The damages in brackets are based on the value of statistical life approach. If this approach was used for the estimation of the total damages mortality damages would account for 98%.

**Table 4.17** Mortality damages of the biogas fuel cycle for Ribe Biogas Plant

| | | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ |
|---|---|---|---|
| YOLL *(VSL)* | low | 14.11 (65.28) | 4.01 (21.59) |
| | mid 3% | 12.87 (64.04) | 3.67 (21.25) |
| | mid 1% | 10.44 (61.61) | 3.00 (20.58) |
| | high | 2.35 (53.52) | 0.76 (18.34) |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

**Table 4.18** Damage costs of the biogas fuel cycle for Ribe Biogas Plant

| | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ | $\sigma_g$ |
|---|---|---|---|
| Power generation | 9.86-20.53 | 2.90-8.95 | A-C |
| Other fuel cycle stages | 6.26-(-16.17) | 1.67-(-7.63) | B-C |
| Subtotal | 16.12-4.36 | 4.57-1.32 | B-C |

Table 4.18 shows a benefit from other fuel cycles in the biogas fuel cycle for Ribe-Nørremark as a result of avoided greenhouse gas emissions. The benefit is larger the larger the value is that has been used for monetisation.

Table 4.19 shows the damage costs per pollutant.

**Table 4.19** Damages by pollutant

| | ECU / t of pollutant |
|---|---|
| $SO_2$ *- YOLL *(VSL)* | 4,400 (13,290) |
| $NO_x$ *- YOLL *(VSL)* | 4,830 (19,020) |
| $PM_{10}$ *- YOLL *(VSL)* | 4,990 (17,900) |
| $NO_x$ (via ozone) | 1500 |
| $CO_2$ | 3.8-18-46-139 |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach

Transportation plays a central role in the biogas fuel cycle, especially for joint biogas plants. The damages from transportation account for more than 30% of the overall damages due to the emission of $NO_x$ during transportation. A reduction in transportation distance will therefore change the impacts from the biogas fuel cycle. However, a comparison of advantages and disadvantages of producing biogas in a joint biogas plant with advantages and disadvantages of the smaller farm biogas plants is complex and not evaluated here.

The estimation of avoided $CH_4$ emissions in the $CO_2$-balance of the biogas fuel cycle is uncertain. The total avoided $CH_4$ emission is based on indications in literature. If the total avoided $CH_4$ emission was twice as high, the benefit of the $CO_2$ balance related to the biogas plant would equal the damages from the whole fuel cycle. On the other hand if the $CH_4$ emission avoided from the storage tanks was not included the overall damages would double.

Another important issue is the emission of unburned carbon at the CHP plant. The biogas is burnt in a gas engine instead of a gas turbine resulting in an incomplete combustion of the gas resulting in large C externalities. The use of gas turbines in biogas plants decreases therefore the external costs considerably.

The amount of unburned carbon in gas engines varies a lot. The number used in the calculation covers CHP plants of 0.5-1 MW, whereas emission of unburned carbon in plants of 1-2MW is double as high. As the present engine is just below 1MW, detailed measurement of the engine could show higher emission of $CH_4$ as the number used is an average for gas engines on the marked. A doubling of this figure would equal the positive balance of the $CO_2$ balance, resulting in an increase of the total damages with more than 50%.

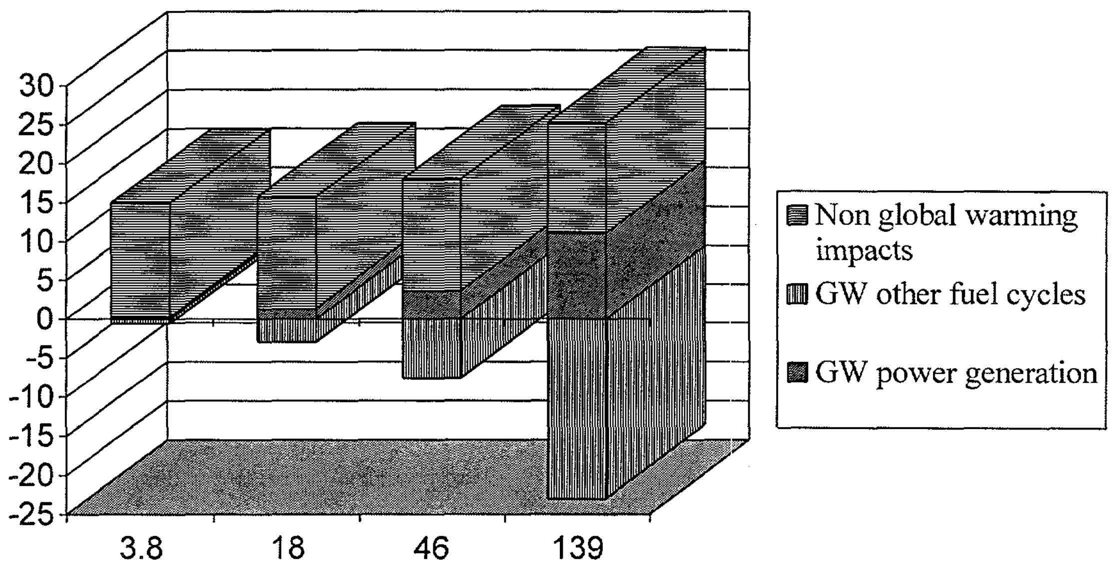


**Figure 4.3** Total damages related to the biogas fuel cycle depending on the $CO_2$ monetisation value

Figure 4.3 shows the total damages related to electricity generation in the biogas fuel cycle. For low monetisation values the non-global impacts are quite dominant, while the total impacts becomes less the larger the monetisation value for $CO_2$ becomes. This is due to the avoided $CO_2$ emissions in the biogas fuel cycle.

# 5. THE WIND FUEL CYCLES, OFFSHORE AND ON LAND

## 5.1 Technology description

The wind farm analysed in the case study is an offshore wind farm consisting of 10 500 kW turbines with a total capacity of 5 MW.

For aggregation it has been necessary also to include a case study for an ordinary wind farm on land. The wind farm that have been chosen is a wind farm consisting of 18 500 kW turbines with a total capacity of 9 MW.

### 5.1.1 The fuel cycle

Wind is a natural energy source, occurring directly at the point of use. Therefore, there is no fuel cycle with fuel extraction, fuel transportation and processing in connection with a wind farm. The wind fuel cycle consists only of the presence of the wind turbines, their operation and connection to the electric grid.

Characteristic for the wind fuel cycle is the lack of pollution connected directly to the wind turbine. However, there is chemical pollution connected to the manufacturing of materials for the turbine itself and the materials used for the electrical transmission equipment. In order to include this chemical pollution the wind turbines are considered from a life cycle analysis (LCA) point of view. The life cycle has the following stages, as shown in Figure 5.1.

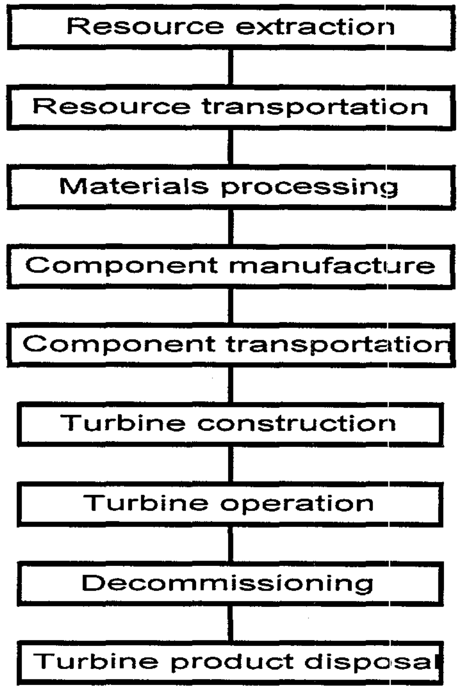


**Figure 5.1** Life cycle of the wind turbine fuel cycle

### 5.1.2 The plants

*Tunø Knob offshore wind farm*

Tunø Knob wind farm is located at a northern geographical latitude of 55.57 degrees and an eastern longitude of 10.21 degrees. The wind farm consists of 10 wind turbines. The turbines are three-bladed Vestas V39 offshore pitch-regulated machines, each with a capacity of 500-kW at a nominal wind speed of 16 m/s. The tower height is 40.5 m and the rotor diameter is 39 m. Technical details are available in appendix XI.

Tunø Knob wind farm is operated by the Jutland electricity company Midtkraft, which is located in Århus; its control centre is located in the village of Hasle outside of Århus.

Each of the wind turbines in the Tunø Knob wind farm has data and transmission equipment, which communicates with the control centre at Midtkraft via radio communication. Wind speed and wind direction and also the electricity production from the wind turbines as well as other data are recorded here.

The wind turbines may be started and stopped from the operational central office at Midtkraft. The wind turbines work fully automatically via stand-alone modes. Each turbine may be operated separately without regard to the others in the farm. Twice a year, technicians for inspecting all the units visit the wind farm.

### *Fjaldene wind farm*

Fjaldene wind farm is located at a northern geographical latitude of 56.9 degrees and an eastern longitude of 8.34 degrees. The wind farm consists of 18 wind turbines placed in two rows with 9 turbines in each row. The distance between the rows is 580 m, while the distance between the wind turbines in the row is 188 m. Each turbine has a capacity of 500 kW. The height of the turbines is 41.5 m. Technical details are available in appendix XI.

The wind farm is connected to the high-voltage grid south of the village of Spjald via a 60/10 kV transformer. 13 of the wind turbines are owned by the electric utility company Vestkraft, while the remaining five units are privately owned. A transformer room is placed close to each turbine, transforming 10 kV to the voltage of the turbine on 690 V.

## 5.1.3 Site description

### *Tunø Knob*

Tunø Knob is located south of Århus Bay. The landscape, which may be affected by the wind farm, is limited by Stavns Fjord at Samsø in the east, and the east coast of Jutland in the west. From Helgenæs in the north to Horsens Fjord, and the islands Endelave and Samsø in the south,(see Figure 5.2).

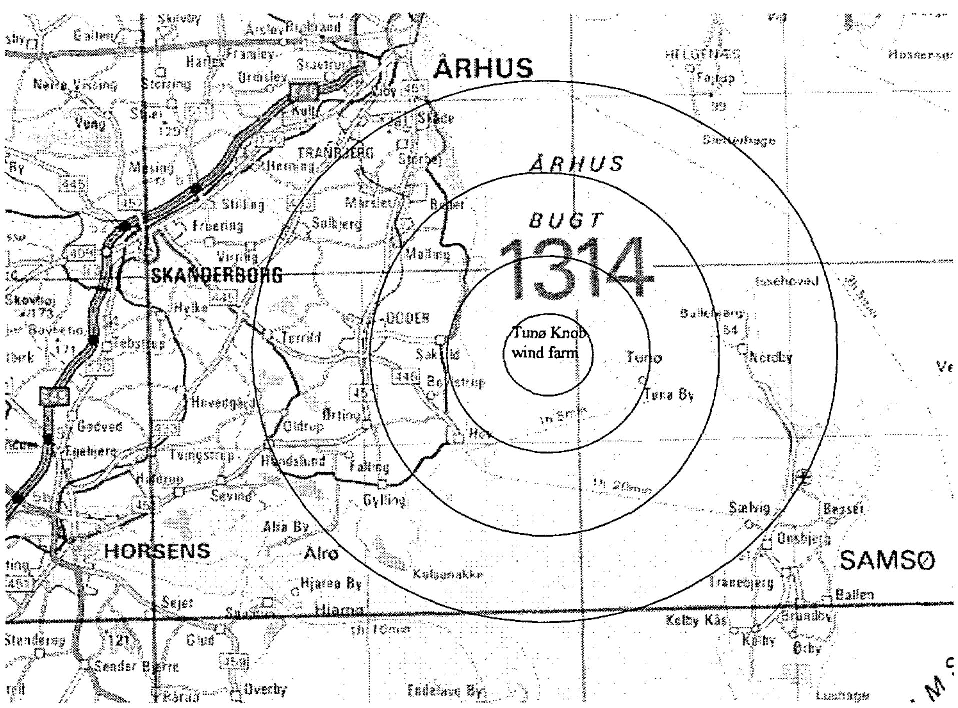


**Figure 5.2** Tunø Knob and its surroundings (1:500,000)

The surrounding landscapes include moraine surfaces and unregularly open, hilly landscapes. The sea area is characterised by the islands and the many bays, inlets and forelands. South of

Århus, at Helgenæs, Tunø and Samsø there are cliffs and slopes towards the sea, which are popular recreational resorts. Along the East Coast of Jutland from Århus to the beach of Saksild there are many popular beaches and areas for summer residents. In the community of Odder live 19,250 people *(Denmark Statistics, 1995).*

On the northwest side of Tunø there is a smaller area for summer residents, located at a distance of 3 km from Tunø Knob. Most of the other locations mentioned are more than 10 km away from Tunø Knob. The stretch from Hov across Saksild Beach to Malling is less than 10 km away from Tunø Knob. Saksild Beach is located 6 km away.

The wind farm is most conspicuous from the western and northwestern part of Tunø. The wind farm is also visible from Saksild Beach and from the top of the hills in the northern part of Samsø.

### *Fjaldene*

Fjaldene wind farm is located in the middle of Jutland, as shown on Figure 5.3. The wind farm occupies an area of about 200 ha.

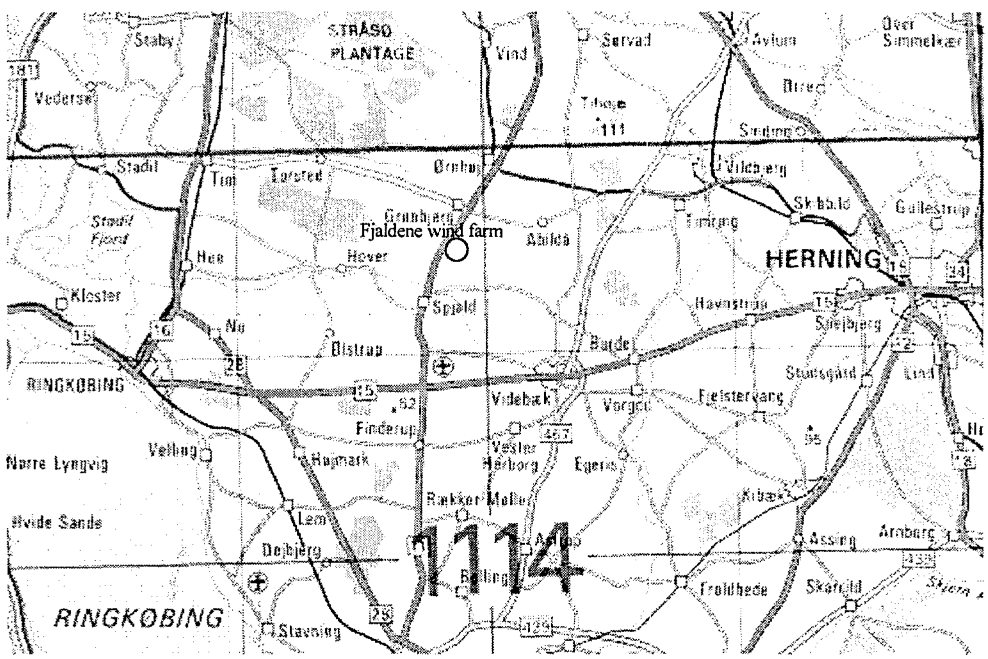


**Figure 5.3** Fjaldene wind farm and its surroundings (1:500,000)

The surrounding landscapes include plantations and irregularly open, hilly landscapes. The wind farm is located on a hill 83 m above sea level, and may therefore be visible for quite a distance compared with wind farms in flat areas. There are three smaller villages at a distance of 3-4 km from the wind farm.

## 5.2 Overview of burdens related to the wind fuel cycle

The impacts from the wind fuel cycle may be divided into impacts due to the use of fossil fuels for the material manufacturing and those due to the presence and operation of the turbine. It is not feasible to include all of the impacts connected to the use of fossil fuels in the assessment of the wind fuel cycle and only the most important of them will therefore be considered.

Acid emissions and greenhouse gases are believed to be the most important environmental burdens from the life cycle assessment.

The impacts may be divided into three subjects:

- Impacts associated with the operation of wind turbines
- Impacts associated with the non-operational stages of the life-cycle of wind turbines
- Impacts associated with the electricity distribution systems for wind turbines

The most relevant environmental burdens due to the full life cycle of the wind turbines and the associated distribution system are summarised in appendix XI.

## 5.3 Selection of priority impacts

For the offshore wind farm in this study the following impacts will be assessed as externalities for the full life cycle of the wind turbines:

- Noise from the turbines
- Visual amenity of the wind farms
- Atmospheric emissions related to material production
- Accidents
- Impacts on birds and shells
- Impacts on fish
- Interference with electromagnetic communication systems

The same impacts are assessed as externalities for the wind farm on land except impacts on fish and interference with electromagnetic communication systems, which are considered irrelevant for the land-based wind farm.

### *Noise from the turbines*

Noise from the wind farm is a burden to the residents and other people in the area close to the wind farm. As Tunø Knob wind farm is located at sea 3 km from land the noise effect is negligible. Still, as noise is the most discussed burden in relation to wind energy this burden is given high priority. Also in the case of Fjaldene wind farm the assessment of noise is quite important.

### *Visual amenity of the wind farms*

Visual intrusion is a burden for residents, visitors, travellers and others near the wind farm. The region of Tunø Knob is a popular one for summer residents and visual intrusion is therefore a burden that has caused a lot of discussion. The visual burden has been given a high priority.

### *Atmospheric emissions related to material production*

There are no atmospheric emissions related to power production using wind turbines. However the production of materials for the wind turbines will cause atmospheric emissions. The materials will mostly be produced by coal and natural gas causing emissions of $SO_2$, $NO_x$, CO and particulates, which will affect human health, materials, agriculture, forests, freshwater and ecosystems.

### *Accidents*

Accidents in the shape of wind blades flying off may cause minor or major injuries or even death to people at a distance from the turbines. As the turbines at Tunø Knob are located at sea the only potential danger would be to sea voyages. The probability that a person in a boat would be struck by a wind blade is almost negligible, and therefore accidents to public health are given low priority.

Accidents may also happen in the road transportation of workers at the wind farm. The wind farms are operated in a remote-control mode from Midtkraft and Vestkraft, and the road transportation relates to the movement of workers from home to the site in the operation of the wind farms at Midtkraft and Vestkraft.

### *Impacts on birds and shells*

The motion of the turbines may cause death, injury or disturbance of birds close to the wind farm. Tunø Knob is located in an area between two larger Ramsar areas with resting eiders at the islet and large passages of birds over the islet. Therefore the effect of the blade rotation is given a high priority.

### *Impacts on fish*

The utilisation of areas at sea for the siting of Tunø Knob wind farm may affect the natural ecosystem and fishes and shells in the area. Current conditions near the wind farm may be changed and the life of shells and fishes in the area may also be changed. Threatened nature types on the seabed may disappear as a consequence of the establishment of the offshore wind farm.

Investigations have been made of the current conditions in the area around Tunø Knob based on earlier hydraulic investigations. The result of these investigations is that the existence of the offshore wind farm will not affect the current conditions. Therefore this impact is given a low priority.

***Interference with electromagnetic communication systems***

Scattering of electromagnetic waves may cause interference for radio and TV users in the vicinity of the wind farm. Residents in the area may not be affected, but scattering of radio waves may be a problem to sailors in the area. Scattering of radio waves is therefore given medium priority.

## 5.4 Quantification of impacts and damages

### 5.4.1 Noise

Only noise in connection with operation of the wind turbines will be considered in this study, as noise from the turbines during operation will affect the largest area over a much longer time than other noise sources in connection with wind turbines.

Noise level and its effect are calculated by a logarithmic formula, which includes the distance from the wind turbine *(CEC,1995f)*. The formula is adjusted for the variation between night and day sensitivity, irregular operation, noise sensitivity of people and background noise. The formula for the annual value of noise, AVN, is as follows:

$$AVN = \sum_{allpositions} (L_{year,obs} - L_{dn,back}) * N_{houses} * A(P) * NDSI$$

Where

$L_{year,\,obs}$ =Average of noise whilst the turbines are in operation over a period of a year

$L_{dn,\,back}$ =Expected noise without the turbines

$N_{houses}$ = Number of houses at that location

A(P) = Annuitised average house price

NDSI = Noise depreciation sensitivity index

As seen from the formula the noise is valued as long as the average of the noise whilst the turbines are in operation is higher than the expected noise without the turbines in a certain distance.

The annual value of noise is calculated to be 967 ECU for Tunø Knob wind farm or 0.004 mECU/kWh. For Fjaldene wind farm the annual value of noise is calculated to be 7,535 ECU or 0.019 mECU/kWh (appendix XI).

### 5.4.2 Visual amenity

Visual amenity is a rather difficult impact to handle; for a wind turbine it is a very individual matter. Some people like the sight of a wind turbine in the nature, while others think that the sight of this same wind turbine destroys the nature.

A survey of house prices has shown a systematic tendency for houses, which are affected by wind turbines on the purchase date, to be cheaper than other houses *(Jordal-Jørgensen, 1995)*, (appendix XI).

The effect on house prices of houses in the vicinity of a wind farm is used as monetisation value for the Fjaldene wind farm. The radius influenced by the wind farm is defined to 1500 meters. Data for monetisation of visibility are shown in Table 5.1.

**Table 5.1** Monetisation of visibility for Fjaldene wind farm

| | |
|---|---|
| Fjaldene wind farm | 18 wind turbines |
| Yearly net electricity production | 19,800 MWh |
| Lifetime | 20 years |
| Number of influenced houses | 7 |
| Effect per wind turbine per house | 527.50 ECU |
| Monetisation of visibility | 0.17 mECU/kWh |

The results are very uncertain. Among others the results from the survey of house prices are based on only three observations. Also the defined radius influenced by the wind farm and thereby the number of houses affected is especially important for the monetisation calculation and can vary the results quite a lot.

In the case of Tunø Knob wind farm both photo- and video-montages have been made. Based on these montages protests have been made before the establishment of Tunø Knob wind farm. The protests were based in particular on both the effects of light from the wind turbines, which could be a disturbance to the nature, as well as noise from the turbines. Today the wind farm is in operation and most of the people in the neighbouring area accept it. There have been no light effects and no noise problems from the wind farm.

Based on these observations visual amenity has been monetised to zero for Tunø Knob wind farm.

### 5.4.3 Impacts of atmospheric emissions

Atmospheric emissions in connection with the wind fuel cycle are especially related to the production of materials for the wind farm. The main materials used for the total wind farms are materials for the wind turbines, materials for fundaments and for the offshore wind farm sea cable materials *(Schleisner et al., 1995)* (details are given in appendix XI).

The relevant atmospheric emissions due to the production of Tunø Knob wind farm and Fjaldene wind farm are shown in Table 5.2 and 5.6*( Fenhann, Kilde, 1994)*.

**Table 5.2** Emissions from the production of Tunø Knob wind farm

| | $SO_2$ (kg) | $NO_x$ (kg) | $CO_2$ (kg) | $N_2O$ (kg) | $CH_4$ (kg) | CO (kg) |
|---|---|---|---|---|---|---|
| Wind turbines | 3888 | 3067 | 1151079 | 35 | 21 | 513 |
| Fundaments | 6175 | 15229 | 4029797 | 95 | 200 | 2999 |
| Sea cables | 1174 | 1153 | 362094 | 11 | 8 | 207 |
| Total | 11238 | 19449 | 5542970 | 141 | 229 | 3718 |

**Table 5.3** Emissions from the production of Fjaldene wind farm

| | $SO_2$ (kg) | $NO_x$ (kg) | $CO_2$ (kg) | $N_2O$ (kg) | $CH_4$ (kg) | CO (kg) |
|---|---|---|---|---|---|---|
| Wind turbines | 6999 | 5520 | 1351116 | 41 | 26 | 788 |
| Fundaments | 5558 | 13706 | 3722776 | 88 | 181 | 2724 |
| Total | 12557 | 19226 | 5331530 | 138 | 212 | 3551 |

### *CO, $SO_2$ and $NO_x$*

Only the impacts associated with emissions of CO, $SO_2$ and $NO_x$ will be assessed here. The emissions divided into those related to electricity, heat and transport due to material production are shown in Table 5.4 for Tunø Knob offshore wind farm and Table 5.5 for Fjaldene wind farm on land (taking the 20-year electricity production into account for both).

**Table 5.4** Emissions of $SO_2$, $NO_x$ and CO in g/kWh for Tunø Knob offshore wind farm

| | $SO_2$ (g/kWh) | $NO_x$ (g/kWh) | CO (g/kWh) |
|---|---|---|---|
| electricity emissions | 0.031 | 0.016 | 0.002 |
| heat emissions | 0.003 | 0.028 | 0.003 |
| transport emissions | 0.011 | 0.032 | 0.010 |
| Total emissions | 0.045 | 0.076 | 0.015 |

**Table 5.5** Emissions of $SO_2$, $NO_x$ and CO in g/kWh for Fjaldene wind farm on land

| | $SO_2$ (g/kWh) | $NO_x$ (g/kWh) | CO (g/kWh) |
|---|---|---|---|
| electricity emissions | 0.023 | 0.012 | 0.001 |
| heat emissions | 0.002 | 0.017 | 0.002 |
| transport emissions | 0.007 | 0.019 | 0.006 |
| Total emissions | 0.032 | 0.048 | 0.009 |

As noted above the above-mentioned emissions are related to production of different materials. A part of the materials are produced in other countries than Denmark, but the emissions mentioned are still based on Danish emission factors.

The damages caused by atmospheric emissions will be calculated using the EcoSense model. The emissions related to electricity production will be based on an average coal-fired plant located in Denmark. Data for the coal-fired plant Fynsværket are used together with Danish meteorological data for production of wind turbines and other materials.

Only the regional module of the EcoSense model has been run, as a part of the emissions arise from other countries. The emissions related to transportation of the material have been excluded, as these emissions are caused mostly by transportation of materials at sea, and cannot be related to energy production from a power plant.

For the emissions related to heat, results from the natural gas fuel cycle of the EcoSense runs have been scaled down to fit the heat emissions for the production of the wind farms.

The total damage in mECU/kWh related to Tunø Knob wind farm is shown in Table 5.6.

**Table 5.6** Total damage in mECU/kWh related to Tunø Knob wind farm

| Receptor | Pollutant | Mid damage |
|---|---|---|
| Crops | $SO_2$, nitrogen / acid deposition | 2 e-4 |
| Human health | tsp, nitrates, sulfates, $SO_2$, $NO_x$, CO | 0.42 |
| Materials | $SO_2$ , wet deposition | 0.01 |
| | Total | 0.42 |

98% of the damages relate to human health. About 48% are caused by $NO_x$ emissions, and 44% by $SO_2$ emissions. 50% of the damages relate to electricity production, and the other half to heat production.

The total damage in mECU/kWh related to Fjaldene wind farm is shown in Table 5.7.

**Table 5.7** Total damage in mECU/kWh related to Fjaldene wind farm

| Receptor | Pollutant | Mid damage |
|---|---|---|
| Crops | $SO_2$, nitrogen/ acid deposition | 3 e-4 |
| Human health | tsp, nitrates, sulfates, $SO_2$, $NO_x$ | 0.22 |
| Materials | $SO_2$ , wet deposition | 80 e-4 |
| | Total | 0.22 |

Detailed data concerning the damages related to atmospheric emissions can be found in appendix XI.

***Ozone***

The damages due to ozone are calculated based on the $NO_x$ emission related to the plant. The following numbers are used for monetisation (appendix II):

**Table 5.8** Monetisation values for ozone

| | | Monetisation value |
|---|---|---|
| Mortality | Europe | 259 ECU/t $NO_x$ |
| | Outside Europe | 153 ECU/t $NO_x$ |
| Morbidity | Europe | 460 ECU/t $NO_x$ |
| | Outside Europe | 272 ECU/t $NO_x$ |
| Crops | Europe | 200 ECU/t $NO_x$ |
| | Outside Europe | 150 ECU/t $NO_x$ |

The $NO_x$ emissions related to production of materials for the wind turbines are assumed to be inside Europe. The $NO_x$ emissions related to production of Tunø Knob are 0.076 g/kWh, while the $NO_x$ emissions related to Fjaldene are 0.048 g/kWh. The damages due to ozone via $NO_x$ are shown in Table 5.9.

**Table 5.9** Damages due to ozone via $NO_x$ emission

| | Tunø Knob | Fjaldene |
|---|---|---|
| Mortality | 0.03 mECU/kWh | 0.02 mECU/kWh |
| Morbidity | 0.06 mECU/kWh | 0.04 mECU/kWh |
| Crops | 0.03 mECU/kWh | 0.02 mECU/kWh |
| Total | 0.12 mECU/kWh | 0.08 mECU/kWh |

***Greenhouse gases***

Like the other atmospheric emissions the emission of greenhouse gases is related to energy use for production of materials for the wind turbines. The emissions from the production of Tunø Knob and Fjaldene wind farms were shown in Table 5.4 and 5.6 respectively. The emissions of $N_2O$, $CH_4$ and CO are converted to $CO_2$ equivalents by the factors: 320, 21 and 1.4 respectively. The total emissions of greenhouse gases for Tunø Knob and for Fjaldene wind farms are shown in Table 5.10 and 5.11 respectively. The emissions have been divided into those related to electricity, heat and transport.

**Table 5.10** Emissions of $CO_2$ in g/kWh for Tunø Knob offshore wind farm

| | $CO_2$ (g/kWh) |
|---|---|
| electricity emissions | 8.428 |
| heat emissions | 11.872 |
| transport emissions | 1.740 |
| Total emissions | 22.040 |

**Table 5.11** Emissions of $CO_2$ in g/kWh for Fjaldene land-based wind farm

| | $CO_2$ (g/kWh) |
|---|---|
| electricity emissions | 6.343 |
| heat emissions | 7.127 |
| transport emissions | 1.065 |
| Total emissions | 14.535 |

The monetisation values used for $CO_2$ have been estimated using the FUND and Open Framework Models (Appendix V). Four different values have been used as seen in Table 5.12.

**Table 5.12** Total damage due to global warming in mecu/kWh related to material production for Tunø Knob and Fjaldene wind farms

| Monetary value for $CO_2$ | Tunø Knob ($mECU/kWh_{el}$) | Fjaldene ($mECU/kWh_{heat}$) |
|---|---|---|
| 3.8 ECU/t $CO_2$ | 0.08 | 0.06 |
| 18 ECU/t $CO_2$ | 0.40 | 0.26 |
| 46 ECU/t $CO_2$ | 1.01 | 0.67 |
| 139 ECU/t $CO_2$ | 3.06 | 2.02 |

### 5.4.4 Accidents

Accidents have impacts on both occupational and public health in relation to production of the wind turbines and transportation of people to and from the wind farms.

***Public accidents***

In the first consideration the amount of public accidents must be site-specific. These are accidents like the detachment of part of a blade, a whole blade or even the whole rotor whilst in motion. This could result in a large object being projected over a considerable distance. The worst case scenario is the runaway of a turbine at wind speeds above the "cut-off", followed by a rapid structural failure in the blade, so that detachment occurs at very high blade speeds *(Taylor and Rand, 1991)*. It has been estimated that such a sequence of events could result in a blade fragment travelling 700 to 800 metres *(UKDEn, 1985; MacQueen et al, 1983)*. However, it seems to be a very unlikely occurrence and that without such runaway conditions the distance could not even approach the range of nearby houses. For the wind farm offshore the risk is even smaller. Therefore, this kind of public accident is not considered as an externality.

Another kind of accident, which here is considered as public, is the road transportation of people working at the wind farm.

The total distance related to the operation of Tunø Knob wind farm is 4030 km pr. year, while the total number of km related to operation of Fjaldene wind farm is 9030 pr. year (appendix XI).

Also, road transportation in relation to the whole life cycle is included in the calculation of public accidents. The total amount of km that relates to construction of Tunø Knob wind farm is 36,000 km. For Fjaldene a total distance related to construction of the wind farm is 24,000 km (appendix XI).

The following accident data are estimated from statistical information over the years 1990-1994: *(Vejtransporten i tal og tekst 1995, Auotomobil-importørernes sammenslutning, 1995) (Denmark Statistics, 1995)*

- Accidents pr. million km of transportation: 0.15
- Killed pr. million km of transportation: 0.009

Using the above-mentioned accidents and an estimate of accident damage valuation at 1,400 ECU for minor accidents, 94,000 ECU for major accidents and 3,100,000 ECU for fatal accidents the damage cost of public accidents is 0.016 mECU/kWh for Tunø Knob off shore wind farm and 0.018 mECU/kWh for Fjaldene wind farm.

***Occupational accidents***

The number of occupational accidents is connected to the production of wind turbines. Occupational accidents in the production of the wind turbines are reported to the responsible agency, and the number of accidents reported for 1995 was 69. The number of wind turbines produced in 1995 was 1545 with a total capacity of 577 MW *(Vindmølleindustrien, 1997)*. Only 6% of these turbines were established in Denmark corresponding to 98 MW; the rest were exported. The accidents per MW are estimated to be 0.12. Seven of the accidents are major ones, while the rest are minor. There are no fatal accidents *(Arbejdstilsynet, 1997)*.

The same estimate of accident damage valuation as for public accidents will be used. With these assumptions, the damage cost of accidents due to the production of Tunø Knob (5 MW, 0.06 major accidents, 0.54 minor accidents) are 0.022 mECU/kWh and 0.025 mECU/kWh for Fjaldene (9 MW, 0.11 major accidents, 0.97 minor accidents).

Also, during the work at sea there may be occupational accidents. Within the establishment of the fundaments at Tunø Knob one diver had an accident. He had encountered physical permanent injuries, and will never be able to dive again.

### 5.4.5 Impacts on birds and shells

The motion of the turbines may cause death, injury or disturbance to birds near the offshore wind farm. The wind farm is located in an area between two larger Ramsar areas with resting eiders at the islet and large passages of birds over the islet. Therefore the motion of turbines is given a high priority.

Many of the birds in the area, especially eiders, use the low water at the islet to find feed and rest. Since February 1994 biologists therefore have examined the life of birds in the area. The investigations are made from two towers for bird counting, one at Tunø Knob, and the other at Samsø. In the small tower at Tunø Knob one or two biologists have been working for some days at a time, registering the number of birds, the dispersion and the behaviour before the establishment of the wind turbines *(Midtkraft, 1995)*.

After establishment of the wind farm the same investigations are made. In this way it is possible to register the change in the bird population at the site, caused by the establishment of the wind farm. Also shells, which are the eiders preferred feed, are observed. One eider may eat one or two kilos of shells a day, and in this way intrusions in the number and behaviour of birds will also influence the amount of shells.

According to these investigations the number of eiders has decreased in the area. However, it is believed that the wind farm not has caused the decrease, as the amount of food for the eiders also has decreased, possibly because of changes in weather conditions.

In relation to birds killed by wind turbines Dutch ornithologists have reported an investigation in the area surrounding five turbines every two days for a year *(Musters et al., 1996)*. There were five turbines and they were in an apparently particularly vulnerable area for the birds - an estuary area with large numbers of bird movements. They found only 26 bodies of which only six were definitely killed by the turbines, three may have been and for eight the cause of death could not be determined. The turbines did definitely not kill the last nine.

Based on the above-mentioned investigation the damage of birds due to wind turbines has been monetised to zero.

### 5.4.6 Impacts on fish

Impacts on fish is an impact, that is related only to an offshore wind farm and not to an ordinary wind farm. In connection with the other Danish offshore wind farm, Vindeby, studies have been made about the fish life before and after the wind farm had been sited. The conclusion of the investigations is that the establishment of an offshore wind farm has not had any negative effect on fishing in the area. The function of the area as a spawn growth area has not been reduced. On the other hand, the number of codfish around the fundaments has increased.

Fauna and flora have been re-established in the plant area. The fundaments of the turbines function now as reef, resulting in an increase of feed for the codfish. There have been no observations of noise or other physical influences from the wind turbines as having an influence on fish in the area.

In this way offshore wind farms have mostly a positive impact on fish, but only very locally, and its impact has therefore been monetised to zero.

### 5.4.7 Interference with electromagnetic communication systems

Scattering of electromagnetic waves may cause burdens for radio and TV users in the area near the wind farm. Residents in the area may not be affected, as they are located at a distance of more than 3 km from the wind farm, but especially for an offshore wind farm scattering of radio waves may be a problem to sailors in the area.

In the ExternE project the interference with electromagnetic communication systems is considered not to be an externality. There may be some smaller problems in connection with microwaves and aviation communication, but these can be avoided by taking care of them in the construction phase of the wind farm. For local television consumers the problem may be solved in a very inexpensive way and is not to be considered as an externality.

However, in the case of an offshore wind farm, the interference with electromagnetic communication systems may affect the communication and navigation systems at sea. It is therefore important to register if the operation of the offshore wind farm will cause any problems. Until now, however, 1½ years after the establishment of Tunø Knob wind farm no effects on the navigation systems have been registered, and the interference with electromagnetic communication systems has therefore been monetised to zero.

## 5.5 Interpretation of the results and sensitivity analyses

The total impacts and damages which have been assessed in relation to Tunø Knob offshore wind farm and Fjaldene wind farm on land are shown in Table 5.13.

In the table the geometric standard deviations $\sigma_g$ for each damage are shown. The labels are:
A = high confidence, corresponding to $\sigma_g$ = 2.5 to 4;
B = medium confidence, corresponding to $\sigma_g$ = 4 to 6;
C = low confidence, corresponding to $\sigma_g$ = 6 to 12;

**Table 5.13** Damages in relation to Tunø Knob offshore wind farm and Fjaldene wind farm on land

| | Tunø Knob mECU/kWh | Fjaldene mECU/kWh | $\sigma_g$ |
|---|---|---|---|
| **POWER GENERATION** | | | |
| Public health (accidents) | 8.9 e-3 | 15.7 e-3 | A |
| Occupational health | ng | ng | A |
| Noise | 4 e-3 | 0.02 | B |
| Visual impacts | 0 | 0.17 | A |
| Impacts on birds | 0 | 0 | A |
| Impacts on fish | 0 | - | A |
| Interference with electromagnetic communication systems | 0 | nq | A |
| **OTHER FUEL CYCLE STAGES** | | | |
| **Material production and manufacture** | | | |
| Public health | | | |
| Mortality*- YOLL *(VSL)* | 0.39 (2.59) | 0.17 (1.36) | B |
| *of which TSP* | *6 e-3 (0.02)* | *4.8 e-3 (0.02)* | |
| $SO_2$ | *0.12 (0.61)* | *0.09 (0.46)* | |
| $NO_x$ | *0.24 (0.89)* | *0.05 (0.17)* | |
| $NO_x$ *(via ozone)* | *0.03(1.07)* | *0.02 (0.71)* | |
| Morbidity | 0.15 | 0.12 | B |
| *of which TSP,* $SO_2$, $NO_x$ | *0.05* | *0.08* | |
| $NO_x$ *(via ozone)* | *0.06* | *0.04* | |
| Accidents | 7.1 e-3 | 2.3 e-3 | A |
| Occupational health | 0.02 | 0.03 | A |
| Crops | 0.03 | 0.02 | B |
| *of which* $SO_2$ | *2 e-4* | *3 e-4* | |
| $NO_x$ *(via ozone)* | *0.03* | *0.02* | |
| Ecosystems | ng | iq | |
| Materials | 0.01 | 8 e-3 | B |
| Global warming | | | C |
| low | 0.08 | 0.06 | |
| mid 3% | 0.40 | 0.26 | |
| mid 1% | 1.01 | 0.67 | |
| high | 3.06 | 2.02 | |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

ng: negligible; nq: not quantified; iq: only impact quantified; - : not relevant

In Table 5.13 the mortality impacts are calculated by using the years of life lost approach. In the case of Tunø Knob global warming accounts for 13% of the damages using the low estimate and as much as 85% using the high estimate. It must be pointed out that these damages are not related to the power production phase, but to the production of materials for the wind turbines.

In the case of Fjaldene mortality accounts for 13% of the damages, and global warming accounts for 58% of the damages using the mid 1% value. In this case, Fjaldene being a wind farm on land visual impacts are important, accounting for 15% of the damages.

Table 5.14 shows the total mortality damages related to the fuel cycle including mortality, morbidity, accidents and global warming. The damages in brackets are based on the value of statistical life approach. If this approach was used for the estimation of the total damages mortality would account for 99% of the damages in the case of Tunø Knob and 90% of the damages for Fjaldene wind farm.

**Table 5.14** Mortality damages of Tunø Knob and Fjaldene wind fuel cycles

| | | Tunø Knob mECU/kWh | Fjaldene mECU/kWh |
|---|---|---|---|
| YOLL *(VSL)* | low | 0.61 (2.80) | 0.38 (1.58) |
| | mid 3% | 0.93 (3.12) | 0.58 (1.78) |
| | mid 1% | 1.54 (3.73) | 0.99 (2.19) |
| | high | 3.59 (5.78) | 2.34 (3.54) |

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

**Table 5.15** Total damages of Tunø Knob and Fjaldene wind fuel cycles

| | Tunø Knob mECU/kWh | Fjaldene mECU/kWh | $\sigma_g$ |
|---|---|---|---|
| Power generation | 0.01 | 0.19 | A-B |
| Other fuel cycle stages | 0.66-3.64 | 0.40-2.36 | B-C |
| Subtotal | 0.67-3.65 | 0.59-2.55 | B-C |

Table 5.15 shows that nearly all the damages from an offshore wind farm are related to the production of the materials for the wind farm. The damages are mostly related to the emissions of $CO_2$ and to some extent $NO_x$ and $SO_2$. For Fjaldene wind farm on land 35% of the damages are damages related to the power generation stage using the low value for $CO_2$.

Figure 5.4 shows the difference in monetised non-global damages for the Tunø Knob offshore wind farm and Fjaldene land-based wind farm. As seen from the figure the damages related to noise and especially visual amenity are much larger for a land-based wind farm than for a sea-based one. For the former noise and visual amenity account for about 39% of the total damages excluding global warming, while these two impacts for the latter account for less than 1% of the total damages.

The damages related to atmospheric emissions are larger for the offshore wind farm than for the other, as the emissions per kWh are larger for the offshore wind farm than for the ordinary wind farm. The reason for this is especially the amount of materials used for foundation and also the material used for the sea cables.

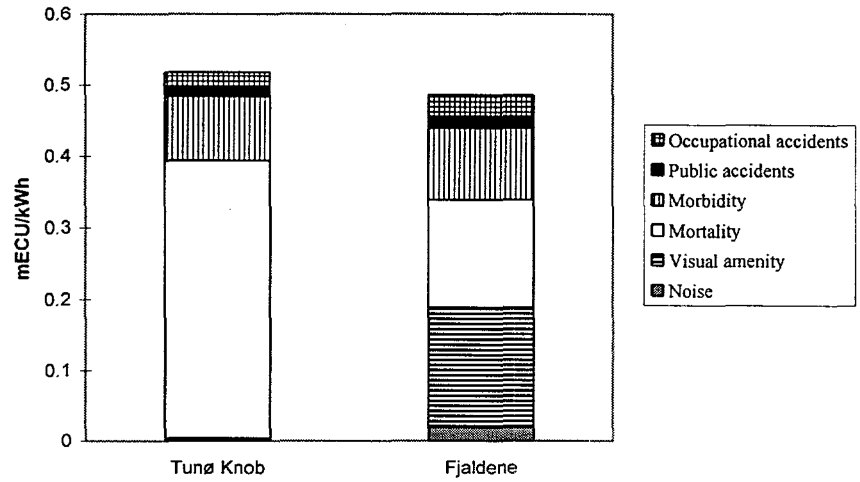


**Figure 5.4** Monetised non-global damages for Tunø Knob and Fjaldene wind farm

However, for Tunø Knob as well as Fjaldene the damages related to atmospheric emissions are dominant (mortality and morbidity) even though the atmospheric emissions are related only to the production phase of the wind turbines.

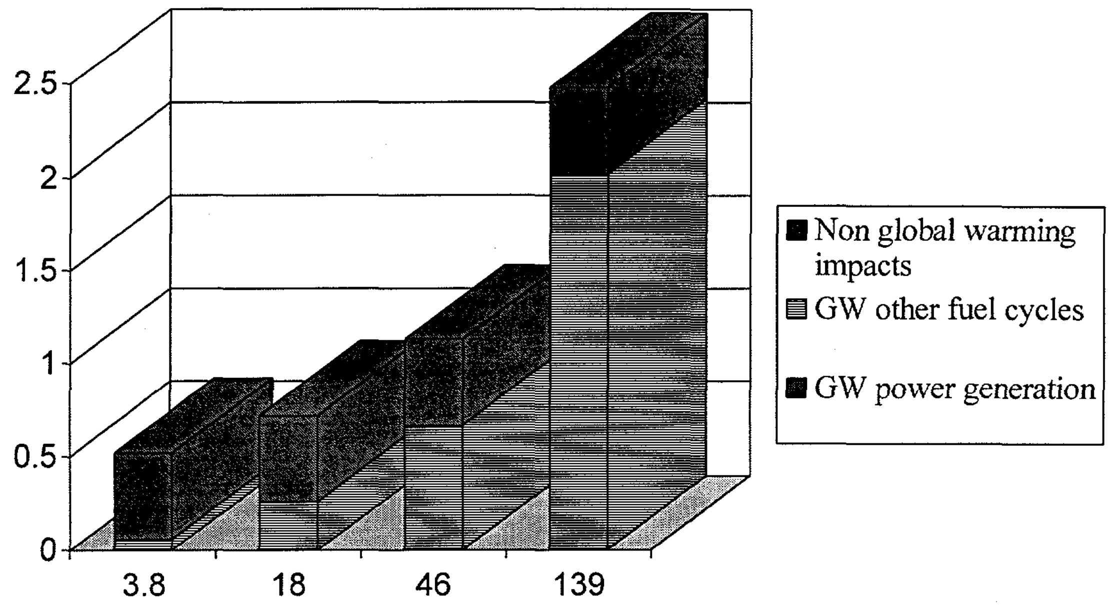


**Figure 5.5** Monetised externalities related to Fjaldene wind farm depending on the values used for monetisation of $CO_2$

Figure 5.5 shows the total monetised externalities related to Fjaldene wind farm on land depending on the monetisation values used for $CO_2$. Using the two lowest values for $CO_2$ monetisation the non-global impacts are still dominants, while global warming becomes dominant using the upper values for $CO_2$.

Damages like noise and visual amenity are very site dependent. Fjaldene wind farm is situated in the middle of Jutland nearby smaller villages. If the wind farm were situated close to town the damages would have been much larger. Figure 5.6 shows the damages due to noise for the Danish, Spanish, English and Greek implementation of ExternE based on calculations from the same formula. The large difference in UK,1 and UK,2 is that UK,1 is situated in the country while UK,2 is situated close to a town.

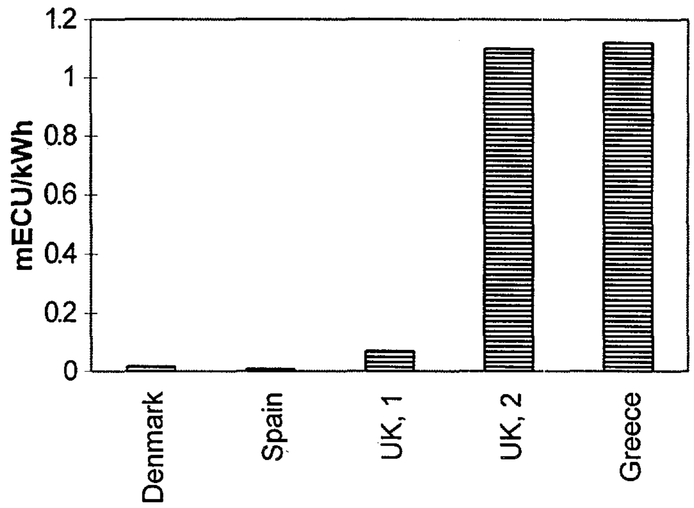


**Figure 5.6** Damages due to noise for the Danish, Spanish, English and Greek implementation of ExternE

The large difference in the noise damages between the countries is also caused by the use of different NDSI values. Using the same values would result in damages as shown in Figure 5.7.

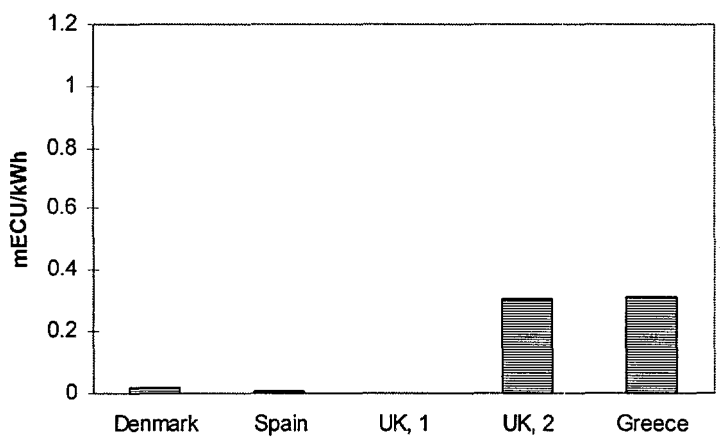


**Figure 5.7** Damages due to noise using same values of NDSI

# 6. AGGREGATION

## 6.1 Comparison of results between fuel cycles

The total damage, which has been assessed, quantified and monetised in relation to the fuel cycles for offshore wind farms, wind farms on land, biogas and natural gas are shown in Table 6.1. For the biogas fuel cycle the atmospheric emissions include emissions due to the transportation of biomass.

The estimates of the externalities of the different fuel cycles are as follows:

- Offshore wind farm: 0.67-3.65 mECU/kWh
- Onshore wind farm: 0.59-2.55 mECU/kWh
- Natural gas CHP plant: 7.11-80.00 mECU/kWh$_{el}$, 1.87-18.50 mECU/kWh$_{heat}$
- Biogas CHP plant: 4.36-16.12 mECU/kWh$_{el}$, 1.32-4.57 mECU/kWh$_{heat}$

The monetisation of impacts due to the wind fuel cycle point at atmospheric emissions from the production of the wind turbines as a major impact. Public accidents as well as occupational health play a minor but still significant role, whereas the impact from noise and visual amenity is very small for the offshore wind farm, but larger for the land-based one.

Impacts from the natural gas fuel cycle relate mainly to emissions directly from the combustion process. Large effects are also due to the risk from gas storage, and there are minor effects on occupational health. Other impacts assessed are negligible.

For the biogas fuel cycle the largest impacts are due to emissions from the combustion process and predominantly the release of $NO_x$. Gas engines typically have a higher emission of $NO_x$ than gas turbines. It should here be emphasised that it is not reasonable to compare the biogas fuel cycle and natural gas fuel cycle directly. Gas engines are preferred for smaller energy demands in local areas, and the biogas engine should rather be compared with another gas engine running on natural gas, taking the energy system advantages and disadvantages into account.

**Table 6.1.** Quantification of damages for an offshore wind farm, a natural gas CHP plant and a biogas CHP plant

| Impact | Wind offshore/on land | Natural gas | Biogas |
|---|---|---|---|
| Noise | 22 summer residents, 1 farm/<br>90 houses, 30 farms | negligible | negligible |
| Visual amenity | negligible/<br>7 houses | 25 houses | negligible |
| Atmospheric emissions | 0.045 / 0.032 g $SO_2$ /kWh<br>0.076 / 0.048 g $NO_x$ /kWh<br>0.015 / 0.09 g CO /kWh | 2.2 mg $SO_2$/$kWh_{el}$,<br>624 mg $NO_x$/$kWh_{el}$,<br>148 mg CO/$kWh_{el}$,<br>0.03 mg TSP/$kWh_{el}$, | 135 mg $SO_2$/$kWh_{el}$<br>3286 mg $NO_x$/$kWh_{el}$ |
| Greenhouse gases | 22 / 15 g $CO_2$ /kWh | 539 g $CO_2$/$kWh_{el}$<br>123 g $CO_2$/$kWh_{heat}$ | -33 g $CO_2$/$kWh_{el}$ |
| Public accidents | 0.0074 / 0.0129 minor accidents<br>0.0101 / 0.0178 major accidents<br>0.001 / 0.0018 death | negligible | 0.21 minor accidents<br>0.29 major accidents<br>0.026 death |
| Occupational accidents | 0.54 / 0.97 minor accidents<br>0.06 / 0.11 major accidents<br>0 death | 24.13 minor accidents<br>3.58 major accidents<br>0.41 death | 5.44 minor accidents<br>0.806 major accidents<br>0.01 death |
| Impacts on birds | negligible | - | - |
| Impacts on fish | negligible | - | - |
| Interference with com. systems | negligible | - | - |
| Gas storage | - | 200 houses | - |
| Land use changes | - | negligible | negligible |
| Emissions to soil | - | | negligible |
| Explosion risk | - | 0.18 minor accidents<br>0.018 major accidents<br>0.0005 death | 0.16 minor accidents<br>0.016 major accidents<br>0.0004 death |
| Road damage | - | - | 210,000 km |

Figure 6.1 shows the most important non-global damages related to the fuel cycles for wind, biogas and natural gas. The figure shows only externalities related to electricity production. For biogas and natural gas, respectively 68% and 78% of the damages are allocated to electricity production; the rest is allocated to heat production using the exergy content of the energy production.

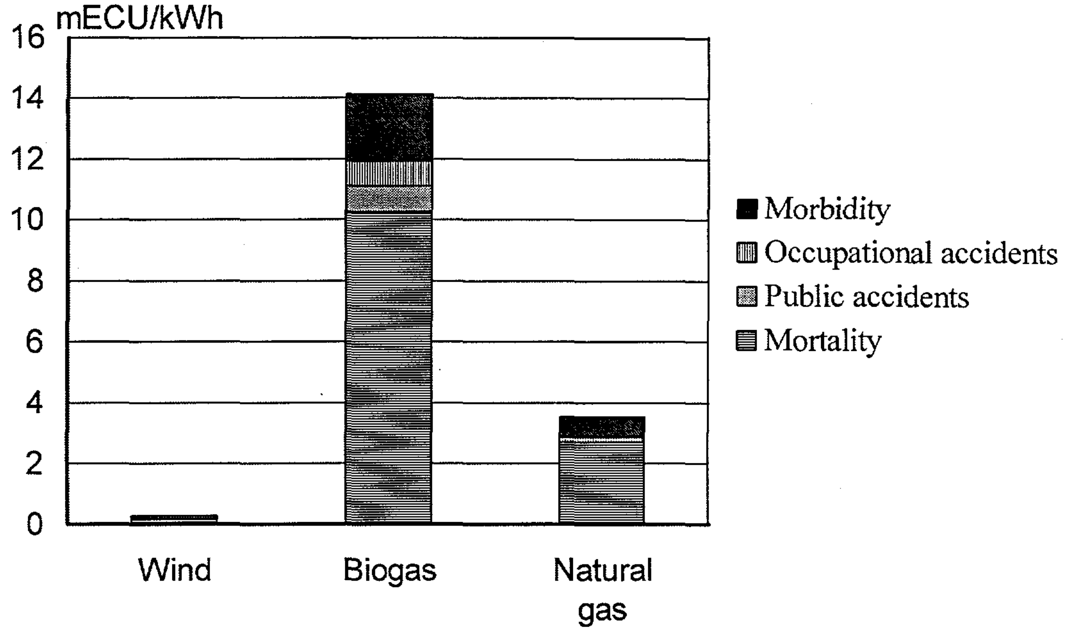


**Figure 6.1** Most important damages related to wind, biogas and natural gas

The atmospheric emissions are the dominant damages for all the fuel cycles. For the life cycle of wind the atmospheric emissions are related only to the production of materials for the wind turbines, while the atmospheric emissions for biogas and natural gas are related to power production. For biogas a smaller fraction of the emissions is related to transportation of biomass.

The atmospheric emissions, not taking $CO_2$ emissions into account, cause damages to crops, forest, human health and materials. Most of the damages, however, are related to human health. For natural gas, for instance, 98% of the damages are related to human health, where the largest part is due to chronic mortality caused by emissions of particulates and nitrates.

## 6.2 Quantified description of the Danish electricity sector

Table 6.2 shows the fuel consumption for power stations producing energy in Denmark in 1995. The large power plants producing electricity as well as heat account for about 75% of the total energy consumption, while the small-scale CHP plants account for 8% of the energy consumption.

**Table 6.2** Fuel consumption for power stations, 1995 *(The Energy Agency, 1996)*

| Direct Energy Content in PJ | Gas/ Diesel / Other oil | Fuel Oil | Orimul-sion | Natural gas | Coal and coke | Wind power | Biomass/ Waste | Biogas | Total |
|---|---|---|---|---|---|---|---|---|---|
| Large Power Stations | | | | | | | | | |
| • Electricity only | 0.11 | 2.15 | - | - | 33.43 | - | 0.08 | - | 35.77 |
| • Heat and Elec. | 1.02 | 7.78 | 19.91 | 10.48 | 218.21 | - | - | - | 257.40 |
| Small-scale CHP . | | | | | | | | | |
| • Electricity only | 0.02 | - | - | - | - | 4.23 | - | - | 4.25 |
| • Heat and Elec. | 0.12 | 0.002 | - | 25.11 | 1.30 | - | 14.02 | 0.69 | 41.24 |
| District Heating | 1.85 | 1.20 | - | 8.86 | 1.57 | - | 19.67 | 0.01 | 33.16 |
| Total | 3.12 | 11.13 | 19.91 | 44.45 | 254.51 | 4.23 | 33.77 | 0.70 | 371.82 |

In 1995 the total energy production from the central power plants and the decentralised power plants was 32201 GWh electricity and 84.4 PJ heat.

The development during the last 20 years in electricity production in Denmark is shown in Figure 6.2. Note that CHP production has become increasingly important in this period.

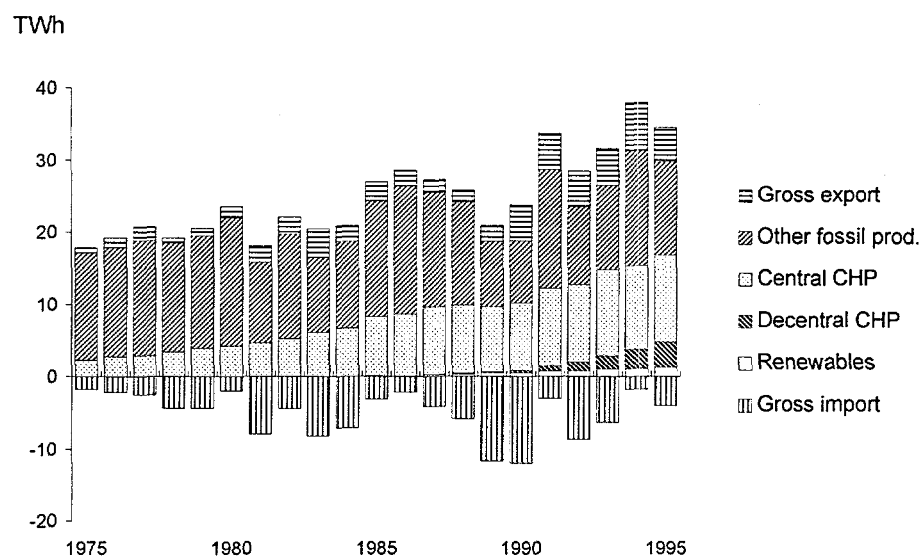


**Figure 6.2** Electricity production in Denmark *(The Energy Agency, 1996)*

Table 6.3 shows the primary energy consumption of central power plants and decentralised power plants divided into fuel consumption. Emissions of $SO_2$, $NO_x$ and $CO_2$ for the different plants are also shown in the table.

**Table 6.3** Primary energy consumption and related emissions, 1995 *(The Energy Agency, 1996)*

| | Primary energy consumption (PJ) | $NO_x$ (ton) | $SO_2$ (ton) | $CO_2$ (kton) |
|---|---|---|---|---|
| Central power plants | | | | |
| • Natural gas | 10.48 | 2516 | 3 | 597 |
| • Coal & coke | 251.54 | 100,658 | 179,746 | 23,906 |
| • Straw/wood | 0.08 | 57 | 11 | |
| • Gas oil /fuel oil | 11.07 | 2671 | 4966 | 863 |
| • Orimulsion | 19.91 | 4778 | 19713 | 1593 |
| Decentralised power plants | | | | |
| • Natural gas | 25.11 | 2511 | 8 | 1429 |
| • Coal & coke | 1.30 | 259 | 756 | 123 |
| • Refuse | 11.52 | 1728 | 1037 | * |
| • Straw/wood | 2.50 | 325 | 64 | * |
| • Biogas | 0.69 | 69 | 0 | * |
| • Gas oil | 0.14 | 14 | 33 | 11 |
| Total | 334.34 | 126,586 | 206,337 | 28,522 |

* $CO_2$ emissions for biogas, refuse and straw and wood are calculated as a total of 1643 kton $CO_2$.

## 6.3 Aggregation methods

The preferred methodology for aggregation is to use an updated version of EcoSense, which is able to include various energy production plants. However, this version of EcoSense is unavailable for the time being, and a simplified methodology for aggregation will be used. The simplified methodology uses the marginal values from ExternE in rather simple calculations to derive aggregate damage values.

For aggregation, the electricity production and combined electricity and heat production are divided into categories, following the plants for which damage costs have been estimated in the Danish implementation. The specification is shown in Table 6.4. District heating plants are not included in the figures for aggregation.

Oil is used mainly as start-up for the coal power plants and therefore emissions from oil consumption are included in the emissions from the coal power plants.

**Table 6.4** Power plants used for aggregation

| Power plants | Fuel | Fuel consumption (PJ) | $NO_x$ (ton) | $SO_2$ (ton) | $CO_2$ (kton) |
|---|---|---|---|---|---|
| Large combined power plants | Coal & oil | 262.61 | 103,300 | 184,700 | 24,800 |
| CHP plants | Natural gas | 35.59 | 5027 | 11 | 2026 |
| Wind power | Wind | 4.23 | - | - | - |
| Biogas CHP plants | Biogas | 0.69 | 69 | 0 | - |
| Total | | 303.12 | 108,396 | 184,711 | 26,826 |

The plants shown in Table 6.4 will be used for aggregation in order to estimate the damage costs for the Danish energy production. The damage costs will in this way be estimated for 82% of the Danish energy production or 90% of the country's electricity production and combined electricity and heat production.

### 6.3.1 Regional damages

The regional scale damages are derived by aggregating from the power plant categories shown in Table 6.4. The regional scale damages are those related to $SO_2$, $NO_x$ and $PM_{10}$ emissions. $PM_{10}$ emissions are not measured in Denmark. For the natural gas fuel cycle and for the biogas fuel cycle the damages related to $PM_{10}$ emissions are negligible compared with the total damages. For the coal fuel cycle the damages related to $PM_{10}$ emissions account for about 3% of the total damages. Based on these observations it seems reliable to ignore the damages related to $PM_{10}$.

For each damage category the marginal damage value in mECU/kWh for the specific plants is converted to a specific damage value in ECU/t. The national emissions are divided into those related to CHP production based on natural gas, large condense power plants based on coal, large combined power plants based on coal and CHP production based on biogas, as shown in Table 6.4. The specific damage values in ECU/t for each pollutant for the specific plants should finally be multiplied by the emissions related to the plant categories. This assumes that the reference power plant values are transferable within the country. For low stacks there may be significant site sensitivity, but for high stacks the sensitivity is small, as the range of these pollutants exceeds the size of all European countries.

The national emissions are derived from national statistics. It is important not to use the emission factors in g/kWh from the reference power plant as a proxy for the whole sector, as the reference plant is very unlikely to be typical for the sector as a whole.

### 6.3.2 Local damages

Local impacts are more difficult to aggregate conveniently as they are more site-specific. The following approaches will be used:

*Occupational health*

For occupational health the damages are related to the reference fuel extraction (mECU/t of fuel extracted). Total damages for power generation for that specific fuel are calculated in ECU/year by multiplying by annual fuel use (in kt). For wind power the external cost per kWh will be multiplied by the total wind energy generated per year.

*Noise and visual damages*

For the Danish implementation of the fuel cycles for coal, natural gas and biogas, noise has been considered to be negligible. Noise for those fuel cycles will therefore be monetised to zero.

For the wind fuel cycle a model for transferring the costs of wind noise has been developed as part of the ExternE Aggregation task. However, this method requires information on population density, source and background noise level, which are data not easily available. Instead, the external cost of noise from the land-based wind farm is used and multiplied by the total wind energy generated (MWh/year) to give the aggregated damages in ECU/year. The same methodology is used concerning visual amenity.

### 6.3.3 Global damages

Global damages are site-independent and will be estimated in the same way as regional damages. The monetisation values used for $CO_2$ have been estimated using the FUND and Open Framework Models (Appendix V). The following four different values have been used: 3.8-18-46-139 ECU/t. In the implementation phase the greenhouse gases have already been estimated as GWP.

## 6.4 Results

Aggregation is carried out for wind power, coal, natural gas and biogas based on the following plants:

- Fjaldene wind farm
- Hillerød CHP plant based on natural gas
- Fynsværk CHP plant based on coal
- Ribe-Nørremark CHP plant based on biogas

### 6.4.1 Wind power

The figures for aggregation related to wind power are shown in Table 6.5.

**Table 6.5** Aggregation data for the wind fuel cycle

| THE WIND FUEL CYCLE- land-based | |
|---|---|
| POWER GENERATION | mECU/kWh |
| Occupational accidents | 0 |
| Public accidents | 14.6 e-3 |
| Noise | 0.02 |
| Visual amenity | 0.17 |
| Impacts on birds | 0 |
| OTHER FUEL CHAIN STAGES | |
| $SO_2$ damages | 0.11 |
| $NO_x$ damages | 0.09 |
| CO damages | 3 e-4 |
| Primary particulate | 0.01 |
| Ozone | 0.08 |
| Global warming | 0.06-2.02 |
| Occupational health | 0.03 |
| Public accidents | 2 e-3 |
| FUEL CYCLE CHARACTERISTICS | |
| POWER STATION | Fjaldene wind farm |
| Capacity | 9 MW |
| Number of turbines | 18 |
| Electricity production per year | 19,800 MWh |
| OTHER FUEL CYCLE STAGES | |
| (production of wind turbines) | |
| S emissions | 0.628 t/year |
| NOx emissions | 0.961 t/year |
| CO emissions | 0.177 t/year |
| Particulate emissions | 2.6 t/year |
| $CO_2$ emissions | 288 t/year |
| Source of fuel | coal / natural gas |

In 1995 the amount of electricity produced by wind power in Denmark was 1180 GWh. Using the above-mentioned figures the damage costs related to the total electricity production based on wind power are 690-3002 kECU/year. In the mid 1% estimate 17% of the damages relate to the power generation phase, while 83 % relate to the production of the wind turbines.

### 6.4.2 Natural gas

**Table 6.6** Aggregation data for the natural gas fuel cycle

| THE NATURAL GAS FUEL CYCLE- | | | |
|---|---|---|---|
| POWER GENERATION | mECU/kWh $_{el}$ | mECU/kWh$_{heat}$ | ECU/t poll. |
| $SO_2$ damages | 0 | 0 | - |
| $NO_x$ damages | 2.95 | 0.82 | 4728 |
| Primary particulate | 0 | 0 | - |
| $CO_2$ | 1.75-63.88 | 0.40-14.58 | 3.8-139 |
| Ozone | 0.94 | 0.25 | 1500 |
| Occupational accidents | 0 | 0 | 0 |
| Public accidents | 0 | 0 | 0 |
| Noise | 0 | 0 | 0 |
| Visual amenity | 0 | 0 | 0 |
| Gas Storage | 1.0 | 0.28 | 5174 ECU/kt gas |
| OTHER FUEL CHAIN STAGES | | | |
| Global warming | 0.30-11.06 | 0.07-2.52 | 3.8-139 |
| Other air emissions | 0 | 0 | 0 |
| Occupational health | 0.14 | 0.03 | 703 ECU/kt gas |
| Public accidents | 0 | 0 | 0 |
| FUEL CYCLE CHARACTERISTICS | | | |
| POWER STATION | | Hillerød CHP plant | |
| S emissions | | 0.684 t/year | |
| $NO_x$ emissions | | 192 t/year | |
| Particulate emissions | | 0 | |
| $CO_2$ emissions | | 177,000 t/year | |
| Efficiency of plant | | 44.4% | |
| OTHER FUEL CYCLE STAGES | | | |
| Source of fuel | | Natural gas | |
| Type of extraction | | Offshore | |
| Transportation details | | Transmission | |
| OTHER IMPORTANT PARAMETERS | | | |
| Offshore extraction and flaring | | 28,400 t $CO_2$/year | |

The data used for aggregation for the natural gas fuel cycle are shown in Table 6.6.

The total damage for natural gas energy production in Denmark is estimated to 45-319 mill. ECU per year. Regional damages relate to atmospheric emissions, especially $NO_x$ and $CO_2$. The damages due to $SO_2$ have been neglected, as this emission is so small that it is very close to the background level. Using the mid 1% estimate (129 mill. ECU) NOx damages are aggregated to 24 mill. ECU, ozone damages to 7.5 mill. ECU and $CO_2$ damages to 93 mill. ECU. Local damages sum up to 5 mill. ECU per year mainly due to gas storage.

### 6.4.3 Coal cycle

The figures used for aggregation related to coal power plants are shown in Table 6.7.

**Table 6.7** Aggregation data for coal power plants

| THE COAL FUEL CYCLE | | | |
|---|---|---|---|
| POWER GENERATION | $mECU/kWh_{el}$ | $mECU/kWh_{heat}$ | ECU/t poll. |
| $SO_2$ damages | 4.09 | 0.70 | 4216 |
| $NO_x$ damages | 6.95 | 1.20 | 3755 |
| primary particulate | 0.48 | 0.08 | 6256 |
| $CO_2$ | 3.4-125 | 0.58-21.4 | 3.8-139 |
| CO | 0.009 | 0.002 | 253 |
| Ozone | 2.77 | 0.47 | 1500 |
| FUEL CYCLE CHARACTERISTICS | | | |
| POWER STATION | | Fynsværket (400 MW) | |
| S emissions | | 2592 t/year | |
| $NO_x$ emissions | | 4945 t/year | |
| Particulate emissions | | 205 t/year | |
| $CO_2$ emissions (estimated) | | 2394 kt/year | |
| Efficiency of plant | | | |
| Other (CO emissions) | | 95 t/year | |

The total coal fuel cycle has not been carried out for Denmark. Estimates for the emissions of a typical coal-fired plant have been made using EcoSense in connection to the wind fuel cycle. These estimates are used for aggregation of power plants based on coal. The regional damages in the coal cycle are attached to $NO_x$, $SO_2$ and $CO_2$. The total damage for the Danish energy sector for coal is thus 1415-4768 mill. ECU. Using the mid 1% estimate (2462 mill.ECU) $CO_2$ accounts for nearly half of the damages related to coal combustion. For $SO_2$ the total damage comes to 778 mill. ECU, for $NO_x$ 388 mill. ECU, ozone 155 mill. ECU and for $CO_2$ 1141 mill. ECU.

Figures for the total emission of particulates and CO are unavailable and the damages for these emissions are therefore not included. The damages related to coal power stations in Denmark are therefore too small. Also the local damages are not included.

### 6.4.4 Biogas

**Table 6.8** Aggregation data for the biogas fuel cycle

| BIOGAS FUEL CYCLE | | | |
|---|---|---|---|
| POWER GENERATION | mECU/kWh$_{el}$ | mECU/kWh$_{heat}$ | ECU/t poll. |
| $SO_2$ damages | 0.24 | 0.07 | 2,880 |
| $NO_x$ damages | 7.14 | 2.02 | 3,370 |
| Primary particulate | 0 | 0 | 3,080 |
| $CO_2$ | 0.3-10.9 | 0.17-6.22 | 3.8-139 |
| $N_2O$ (ozone) | 2.10 | 0.59 | 1500 |
| Occupational accidents | 0 | | |
| Noise | 0 | 0 | 0 |
| Visual amenity | 0 | 0 | 0 |
| OTHER FUEL CHAIN STAGES (mainly transportation) | | | |
| Global warming | -0.63-(-23.06) | -0.26-(-9.56) | 3.8-139 |
| Other air emissions: | | | |
| $NO_x$ | 3.38 | 0.95 | 3,100 |
| $SO_2$ | 0.19 | 0.05 | 2,990 |
| Ozone | 0.77 | 0.22 | 1500 |
| Occupational health | 0.82 | 0.23 | 56.3 mECU/GJ |
| Public accidents | 0.83 | 0.23 | 74.7 mECU/GJ |
| Road damage | 0.61 | 0.17 | 126 mECU/GJ |
| FUEL CYCLE CHARACTERISTICS | | | |
| POWER STATION | Ribe-Nørremark CHP plant | | |
| S emissions | 0.720 t/year | | |
| $NO_x$ emissions | 13.20 t/year | | |
| Particulate emissions | $0.14*10^{-3}$ t/year | | |
| $CO_2$ emissions (total for the fuel cycle) | -1132 t/year | | |
| Efficiency of plant | 32% | | |
| OTHER FUEL CYCLE STAGES | | | |
| Source of fuel | North Sea | | |
| Type of extraction | Drilling | | |
| Transportation details (total emissions, transportation) | 6.9 t - $SO_2$ - $NO_x$/year | | |

Table 6.8 shows the data used for aggregation for the biogas fuel cycle. The only regional damages for the biogas fuel cycle are those due to $NO_x$ emission. The total aggregated damage is 762 kECU including damage from transportation assuming a similar transportation pattern at the other biogas plants. The total aggregated damage is calculated only based on the $NO_x$ emissions, ozone, accidents and road damages. This means that the positive effect of $CO_2$ emissions has not been taken into account.

66% of the damages are related to $NO_x$ and ozone emissions. Aggregating the occupation and public damages the total damage will be 91.6 kECU. Aggregated road damages will lead to a total road damage of 86,9 kECU. No total value for $SO_2$ emissions has been available, but assuming similar emissions at the other biogas plants the damage would be 80 kECU per year.

### 6.4.5 Summary of aggregation results

The results of the aggregation for the energy sector in Denmark are shown in Table 6.9. The aggregated damages in kWh are only related to the power generation stage.

**Table 6.9** Summary of aggregation results

| SUMMARY OF AGGREGATION RESULTS | | | | |
|---|---|---|---|---|
| ENERGY MIX | | GWh/year | % | |
| Coal | | 70,825 | 75% | |
| Natural gas | | 9,965 | 10% | |
| Oil | | 3,140 | 3% | |
| Wind | | 1,180 | 1.2% | |
| Orimulsion | | 5,575 | 6% | |
| Biomass /waste | | 3,950 | 4.2% | |
| Biogas | | 195 | 0.2% | |
| Other renewables | | 58 | 0.1% | |
| *Total for aggregation* | | 85,305 | 89.4% | |
| Damages by pollutant | ECU/t of pollutant | | | |
| | $SO_2$ | $NO_x$ | $CO_2$ | Ozone |
| Coal & oil | 4216 | 3755 | 3.8-139 | 1500 |
| Natural gas | - | 4728 | 3.8-139 | 1500 |
| Wind | - | - | - | - |
| Biogas | 4400 | 4830 | 3.8-139 | 1500 |
| Aggregated damages using different $CO_2$ monetisation values (ECU/t $CO_2$) | ECU/year (3.8) | ECU/year (18) | ECU/year (46) | ECU/year (139) |
| Coal & oil | 1415 mill. | 1767 mill. | 2462 mill. | 4768 mill. |
| Natural gas | 45 mill. | 72 mill. | 129 mill. | 319 mill. |
| Wind | 0.69 mill. | 0.92 mill. | 1.4 mill. | 3.0 mill. |
| Biogas | 0.76 mill. | 0.76 mill. | 0.76 mill. | 0.76 mill. |
| TOTAL | 1461 mill. | 1841 mill. | 2593 mill. | 5091 mill. |

Aggregation has been carried out for coal and oil together (as oil is mostly used for starting up on coal-fired plants), for natural gas, for wind and for biogas. These fuels cover totally 89.4% of the fuels in the energy sector, excluding district heating.

The table shows a total damage of 1461-5091 mill. ECU for the energy sector per year depending on the monetisation value used for $CO_2$. Coal and oil accounts for close to 95% of the total, although these fuels only cover 87% of the total amount of fuels that have been aggregated. The damage costs for natural gas are much smaller than for coal, primarily because there are no $SO_2$ emissions. The estimates for the coal fuel cycle are based on a fired plant equipped with desulphurisation plant as well as de-$NO_x$ burners. For plants without this equipment the damage costs would be much higher.

# 7. CONCLUSIONS

The major result of this study is that, in spite of the uncertainties underlying the analysis, a large set of externalities for electricity generation has been calculated. Therefore, a first attempt towards the integration of environmental aspects into energy policy may be carried out, taking into account all the limitations, which will be explained later.

It has to be reminded that the technologies assessed for individual fuel cycles are state-of-the-art technologies, equipped with environmental devices. In the case of the natural gas fuel cycle, for example, even though the gas turbine is equipped with a specific technology for reducing the $NO_x$ emission, 98% of the externalities estimated are related to $NO_x$ emissions. If older technologies are considered the externality per kWh may rise to quite high values.

For the biogas fuel cycle the externalities are estimated to be rather high if not the avoided $CO_2$ emissions were taken into account. The reason for this is that gas is burnt in a gas boiler instead of a gas turbine resulting in an incomplete combustion of the gas resulting in large $NO_x$ externalities. The use of gas turbines in biogas plants will therefore decrease the external costs considerably. This illustrates the uncertainty in using external costs estimated for one specific plant to be used as a number for externalities in energy policy.

Also it has to be reminded that the methodology has still a large number of uncertainties.

These uncertainties create also some difficulties for using the results directly for policy-making. Several aspects should be improved, such as for instance the atmospheric dispersion models. An important issue, which should also be studied, is the relationship between atmospheric pollution and chronic mortality.

Considering that chronic mortality is, by large, the major externality of fossil fuel cycles, the fact that there is only one exposure-response function for its estimation, and that this function comes from the US, without being checked in Europe, adds a lot of uncertainty to the final results.

The valuation of human life is also a significant factor affecting the results, as it determines the human health externality, which, as said before, is the major one. Controversy still exists around this issue, and, in spite of the modifications introduced in the valuation of life by the Core Project, the values assigned are still contested outside the project.

All these uncertainties affect the individual fuel cycles examined. For the aggregation of results to the whole electricity sector, more problems arise, such as the transferability of results from one site to another, or the accounting of effects for which there is a threshold. Indeed, differences in the damages per t of pollutant emitted between different sites are quite large, so the direct transfer of results from one site to another is not reasonable.

Hence, it is recommended to use the results provided by this report only as background information. This background information might be very useful for establishing economic incentives, such as environmental taxes, or subsidies for renewable energies, or for energy planning measures. However, as said before, results should not be used directly, until the methodology is refined.

For what results may be used directly, though, is for planning processes where the quantitative results are not so relevant. This is the case, for example, of the optimisation of plant site selection, or for choosing among different energy alternatives. Another possible use of these results is the analysis of the costs and benefits of the implementation of environmentally friendly technologies.

Although further research is required to refine the methodology, and thus, to produce more precise results, removing the existing uncertainties, this report is the first comprehensive attempt to estimate the externalities of electricity generation in Denmark using a common EU methodology. Hence, it is believed that it will contribute to a large extent to the integration of environmental aspects into energy policy.

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Abstract (max. 2000 characters)

The objective of the ExternE National Implementation project has been to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The tasks include the application of the ExternE methodology to the most important fuel cycles for each country as well as to update the already existing results; to aggregate these site- and technology-specific results to more general figures.

The current report covers the results of the national implementation for Denmark. Three different fuel cycles have been chosen as case studies. These are fuel cycles for an offshore wind farm and a wind farm on land, a decentralised CHP plant based on natural gas and a decentralised CHP plant based on biogas. The report covers all the details of the application of the methodology to these fuel cycles and aggregation to a national level.

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